# The Atom

TOPIC 1

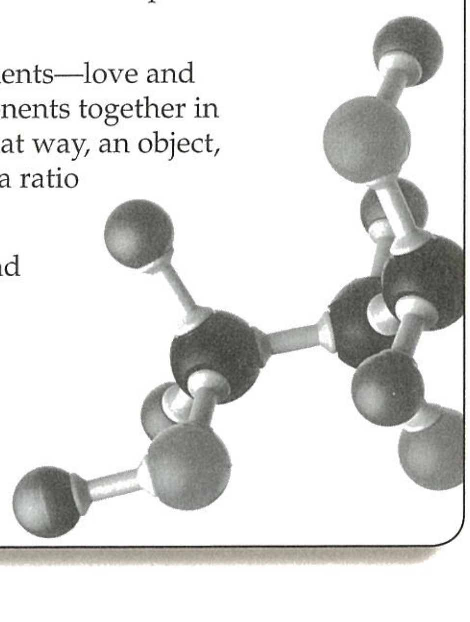
## How Scientists View Atomic Composition

***Look at your desk. What do you think it is made of?***

You might say wood, metal, or plastic. If you were living in Greece 2500 years ago, you would have said "earth." At that time, the Greek philosopher Empedocles claimed that all matter was composed of fire, air, water, and earth.

Empedocles also described two other components—love and discord. It was love that held the other components together in matter and discord that kept them apart. In that way, an object, substance, or organism could be described as a ratio of fire, air, water, earth, love, and discord.

These components were considered eternal and could not be explained. Yet about 2000 years later, scientists did begin to explain them and the nature of matter itself.



TOPIC 1

# The Atom

**Vocabulary**

| | | |
|---|---|---|
| atom | excited state | neutron |
| atomic mass | ground state | nucleus |
| atomic mass unit | heterogeneous | orbital |
| atomic number | homogeneous | proton |
| compound | isotope | pure substance |
| electron | mass number | valence |
| element | mixture | wave-mechanical model |

## Topic Overview

Chemistry is the study of matter, which is anything that has mass and volume. The desk that you are sitting at, the air around you, and your body are all made up of matter. Chemistry deals with the composition of matter and the changes that matter may undergo.

Scientists have long sought the answers to solve the question, "What are we, the earth, and the stars made of?" Our present answer is that there are only about 100 different building blocks that explain the composition of the entire visible universe. Our present model has been the result of the thinking and experiments of scientists over a few thousand years. Today's model adequately explains how so many different objects can be made from such a few fundamental building blocks. These fundamental particles, called atoms, are themselves made of even smaller parts.

## Early Studies of Atoms

The Greeks' view of the nature of matter as being composed of fire, air, water, and earth lasted until the 1600s when Robert Boyle identified gold and silver as themselves being elemental; that is, they are not themselves made of fire, air, earth, or water. As Boyle's ideas were slowly accepted, additional elements were discovered, and the Greek concept of what makes up matter faded.

### Dalton's Atomic Theory

The work of Boyle led John Dalton to propose his revolutionary theory in the 1700s. He theorized that the basic unit of matter is a tiny particle called an **atom.**

Dalton's theory of the atom can be summarized by the following points.

- All elements are composed of indivisible atoms.
- All atoms of a given element are identical.

- Atoms of different elements are different; that is, they have different masses.
- Compounds are formed by the combination of atoms of different elements.

Although we now know that some of Dalton's theory was not correct, it laid the important groundwork for the current concept of the atom.

## Structure of the Atom

Experimental studies of the atom soon showed that it was not indivisible but was made up of even smaller parts.

**Electrons** J. J. Thomson used a cathode ray tube to show one of these smaller units that make up an atom. Because the ray produced in the tube was deflected a certain way by an electrical or magnetic field, he concluded that the ray was formed by particles and that the particles were negatively charged. The only source available for the particles was the atoms present. Thus, Thomson theorized that an atom contains small, negatively charged particles, which he named **electrons.**

A concept of the atom developed in which these negatively charged particles were visualized as being embedded in atoms, just as we might find raisins in bread. This model was called the "plum pudding" model. In this model, the mass of the rest of the atom was evenly distributed and positively charged, taking up all of the space not occupied by the electrons.

**The Nucleus** If electrons are present in atoms, what makes up the rest of the atom? One scientist who studied this question was Ernest Rutherford. A group of scientists that included Rutherford conducted the following experiment, with surprising results. Look at Figure 1-1A. They directed alpha particles, which are positively charged particles that are much smaller than an atom, at a thin piece of gold foil. If the plum pudding model of the atom were correct, all of the alpha particles would pass through the foil with just a few being slightly deflected.

As the scientists expected, most of the particles passed straight through the foil, and a few were slightly deflected. But to their amazement, some of the alpha particles were greatly deflected, and some even bounced back, as shown in Figure 1-1B. From this experiment, Rutherford concluded that atoms have a dense central core, called a **nucleus,** while the remainder of the atom is essentially empty space. Because alpha particles are positively charged and

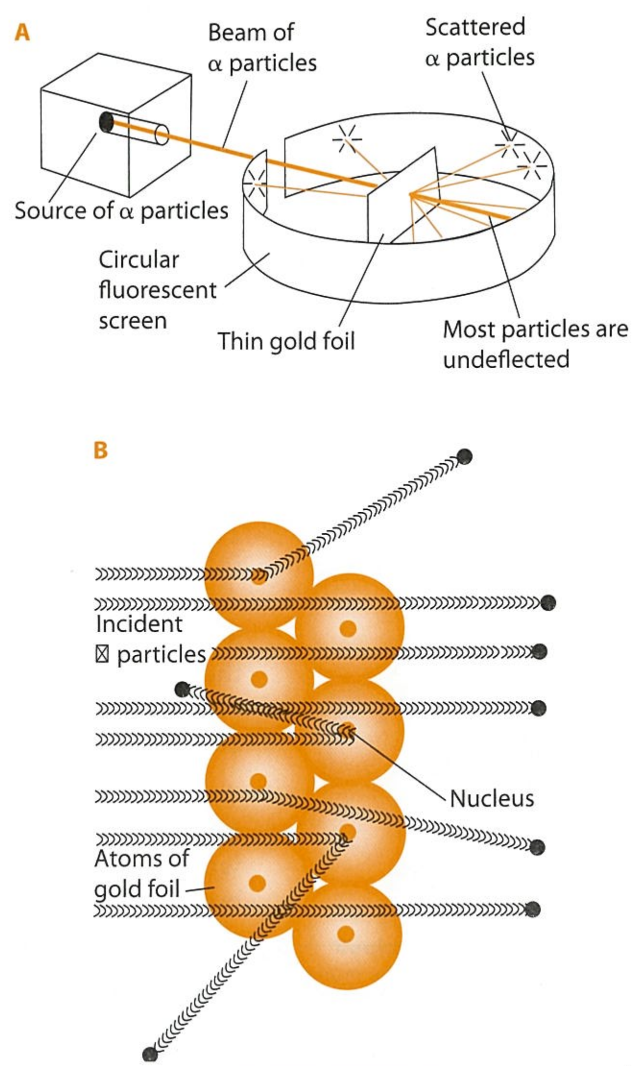



**Figure 1-1. The Rutherford gold-foil experiment:** (A) Scattering of alpha particles (B) The deflections of the alpha particles showed that atoms have a dense, positively charged center. Experimental results showed that only about one alpha particle out of each 10,000 was dramatically deflected.

were repelled by the nucleus, the nucleus must also be positively charged because like charges repel each other.

**Protons and Neutrons** Since atoms are electrically neutral, scientists reasoned that there must be positive charges to offset the negatively charged electrons, and these charges must be located in the nucleus. These positively charged particles are called **protons.** In addition to protons it was later discovered that there are additional particles in the nucleus that do not have either a positive or negative charge. These neutral particles are called **neutrons.**

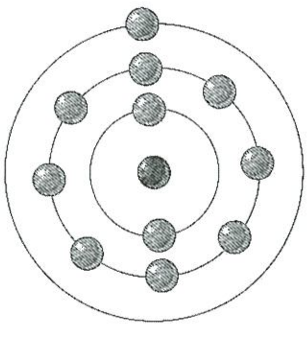


**Figure 1-2. The Bohr model of the atom:** Protons and neutrons are in the dense central nucleus with electrons orbiting in valence shells.

## Modern Atomic Theory

Scientists used the information derived from this and other experiments to further describe atomic structure.

**The Bohr Model of the Atom** In the early 20th century the common model of the atom was the Bohr or "planetary" model. The model showed a center, the nucleus, and rings of orbiting electrons.

Normally, composition of the nucleus shows the number of positively charged protons and the number of neutral neutrons present as shown in Figure 1-2. The electrons are shown in concentric circles or shells around the nucleus, designated by the letters K, L, M, N, O, P, and Q or the numbers 1 through 7. The K shell can hold a maximum of 2 electrons, the L shell a maximum of 8. The outermost shell of an atom may not contain more than 8 electrons. These outermost electrons are called **valence** electrons.

When a valence shell is filled, the element is a noble gas. When a shell is filled, the next element begins to fill the next higher energy valence shell.

The same information can be shown in a linear form. The symbol of the element is followed by showing the number of electrons in each succeeding shell. Thus Na-2-8-1 represents the sodium atom. The "Na" represents the nucleus and the 2-8-1 shows the electron arrangement in the K, L, and M shells. The electron structure of each element is shown on the Periodic Table of the Elements in the *Reference Tables for Physical Setting/Chemistry*. (R)

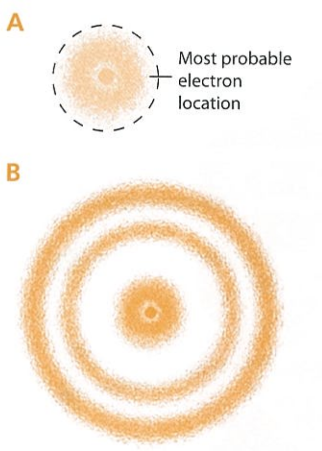



**Figure 1-3. Electron cloud model of the atom:** The modern model of the atom shows a dense nucleus. (A) In this diagram of hydrogen, each dot represents a possible location for the electron. The ring shows the most probable location of an electron. (B) In this model of a cross-section of a multielectron atom, the dots represent probable locations of electrons. Each of the darker circles represents an orbital.

**The Wave-Mechanical Model** Advances in the study of energy aided in modifying the atomic model. Energy had been viewed as being waves, and matter as particles. By the 1900s, energy and matter were both viewed as acting as both waves and particles. The wave aspect of nature was expanded, and it was also proposed that energy was made up of tiny packets called quanta. These energy packets acted like particles.

When it was later determined that the electron not only has properties of mass but also has wavelike properties, this concept of a dual nature was incorporated into the current model of the atom, the **wave-mechanical model.** This modern model of the atom pictures the atom as having a dense, positively charged nucleus as proposed in the planetary model. The major difference between the wave-mechanical model and the Bohr model is found in the manner in which the electrons are pictured. Instead of moving in definite, fixed orbits around the nucleus as suggested in the Bohr model, the wave-mechanical model portrays electrons with distinct amounts of energy moving in areas called orbitals. An **orbital** is described as a region in which an electron of a particular amount of energy is most likely to be located. Models of orbitals are shown in Figure 1-3.

Thus, the modern model of the atom is not the invention of a single scientist, but rather one that has evolved over a long period of time. Figure 1-4 summarizes some of the atomic models involved in the evolution of the current atomic model.

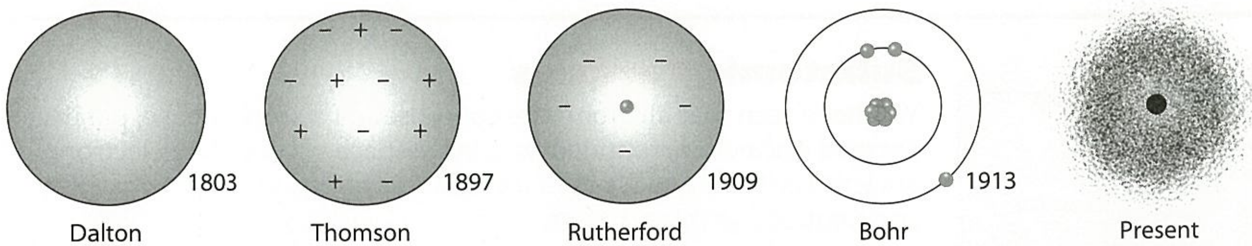



**Figure 1-4. Changing views of atomic structure over time: The representations show the cannonball, plum pudding, nuclear, planetary, and wave-mechanical atomic models.**

## Review Questions — Set 1.1

**1.** The concept that matter is composed of tiny, discrete particles is generally attributed to the

(1) Greeks
(2) Romans
(3) English
(4) Germans

**2.** The first subatomic particle discovered was the

(1) proton (3) electron
(2) neutron (4) photon

**3.** Which statement describes the distribution of charge in an atom?

(1) A positively charged nucleus is surrounded by one or more negatively charged electrons.
(2) A positively charged nucleus is surrounded by one or more positively charged electrons.
(3) A neutral nucleus is surrounded by one or more negatively charged electrons.
(4) A neutral nucleus is surrounded by one or more positively charged electrons.

**4.** In the wave-mechanical model of the atom, an orbital is the most probable location of

(1) a proton. (3) a neutron.
(2) a positron. (4) an electron.

**5.** The model of the atom that pictured the atom with electrons stuck randomly throughout the mass of the atom was called the

(1) cannonball model
(2) plum pudding model
(3) planetary model
(4) wave-mechanical model

**6.** After bombarding a gold foil sheet with alpha particles, scientists concluded that atoms mainly consist of

(1) electrons
(2) empty space
(3) protons
(4) neutrons

**7.** Experimental evidence indicates that the nucleus of an atom

(1) contains most of the mass of the atom
(2) contains a small percentage of the mass of the atom
(3) has no charge
(4) has a negative charge

8. Dalton's atomic theory states that
   (1) all atoms of an element are positively charged
   (2) different elements can have the same mass
   (3) atoms of a given element must be identical
   (4) all the atoms in a compound are identical

9. Modern theory pictures an electron as
   (1) a particle only
   (2) a wave only
   (3) both a particle and a wave
   (4) neither a particle nor a wave

10. Which statement is most consistent with the plum pudding model of the atom?
   (1) Electrons occupy regions of space.
   (2) Negative particles orbit a positive nucleus.
   (3) The atom consists of mostly empty space.
   (4) Negative particles are embedded in atoms.

11. Why did Rutherford conclude that the atom was mostly empty space?

12. What is a major difference between the Rutherford and the wave-mechanical models of the atom?

## Subatomic Particles

You have seen that all atoms are composed of a small, dense, positively charged nucleus surrounded by a large space occupied by electrons. The nucleus contains two types of particles—protons with a positive charge, and neutrons with no charge.

Protons have a mass of only $1.67 \times 10^{-24}$ g. Because the mass of a proton is so small, it is more convenient to use a different scale whose units are called **atomic mass units** to represent its mass. A proton is assigned 1.0 atomic mass unit (amu). A neutron has approximately the same mass as a proton.

Each atom of a specific element must contain the same number of protons as every other atom of that element. The number of protons in the nucleus of an atom is the **atomic number** of that element. For example, chlorine has an atomic number of 17. Each chlorine atom contains 17 protons in its nucleus.

Electrons occupy the space of an atom outside the nucleus and have a charge equal to, but opposite of, a proton. Electrons are much less massive than either the proton or neutron, having a mass of only 1/1836 amu. Table 1-1 summarizes information about each of the particles that make up an atom.

It has been mentioned that the mass of an atom is extremely small. The atomic mass scale replaces grams as the unit used to describe the masses of atoms. The nucleus of a carbon atom containing 6 protons and 6 neutrons is taken as the standard mass, and the mass of any atom is a ratio between its mass and that of the carbon nucleus. The sum of the numbers of protons and neutrons in the nucleus is called the **mass number** of the nucleus. Thus, a nucleus with 7 protons and 7 neutrons has a mass number of 14. When determining the mass of an atom, the mass of the electrons is so small it is not considered in the calculation.

### Digging Deeper

The concept of protons, electrons, and neutrons as fundamental particles can be used to explain most of the chemical behavior of an atom. However, recent research has shown that protons and neutrons are themselves made of smaller particles called quarks. Each quark has a fractional charge of either $\frac{2}{3}+$ or $\frac{1}{3}-$. Each proton and neutron is composed of three quarks. Because it has a total 1+ charge, a proton must be composed of two quarks each with a charge of $\frac{2}{3}+$ and one quark with a charge of $\frac{1}{3}-$. A neutron has no charge, so it must be composed of one quark with a charge of $\frac{2}{3}+$ and two quarks each with a charge of $\frac{1}{3}-$.

**Table 1-1. Some Subatomic Particles**

| Particle | Charge | Mass | Location | Symbol |
|---|---|---|---|---|
| Proton | 1+ | 1 amu | nucleus | ${}^{1}_{1}H$ or $p^{1}_{1}$ |
| Neutron | 0 | 1 amu | nucleus | ${}^{1}_{0}n$ |
| Electron | 1− | 1/1836 amu | outside | ${}^{0}_{-1}e$ |

| Table 1-2. Isotopes of Hydrogen | | | | |
|---|---|---|---|---|
| Particle | Protons | Neutrons | Mass Number | Symbol |
| Protium | 1 | 0 | 1 amu | ${}^{1}_{1}H$ |
| Deuterium | 1 | 1 | 2 amu | ${}^{2}_{1}H$ |
| Tritium | 1 | 2 | 3 amu | ${}^{3}_{1}H$ |

**Isotopes** Although all the atoms of a given element must contain the same number of protons, the number of neutrons may vary. Most atoms of hydrogen contain only a proton. Remembering that the mass number of an atom is the sum of its protons and neutrons, this atom of hydrogen has a mass of 1 amu. In addition to this atom with a mass of 1 amu, there are some atoms of hydrogen that have a nucleus with both a proton and a neutron. While this is still an atom of hydrogen, it has a mass number of 2. There is still another type of hydrogen with a nucleus containing two neutrons in addition to a proton; this atom has a mass number of 3. These different forms of an atom are called isotopes. **Isotopes** are atoms of the same element that have different numbers of neutrons, and hence have different mass numbers. Table 1-2 describes the isotopes of the element hydrogen.

| | |
|---|---|
| C-14 | ${}^{14}C$ |
| Carbon-14 | ${}^{14}_{6}C$ |

**Figure 1-5. Some symbols of isotopes:** Common isotopic notations of carbon atoms that contain six protons and eight neutrons

**Isotope Symbols** Isotopes can be identified by using a symbol that indicates both the element and its mass number. Thus, C-12 represents a carbon atom with a mass number of 12. The mass number represents the sum of the protons and neutrons. The difference between the atomic number of an atom and its mass number is the number of neutrons. Because the atomic number (number of protons) of C-12 is 6, the number of neutrons will also be 6. Different ways to symbolize carbon-14 isotopes are shown in Figure 1-5.

## Atomic Masses

You have seen that the mass number of a given nucleus must be an integer because it is the sum of the numbers of protons and neutrons in the nucleus. However, when you examine the periodic table of the elements, you will notice that most of the elements have masses that are fractional values. These masses are called the **atomic masses** of the elements, and they are the average mass of all the isotopes in a sample of the element.

### SAMPLE PROBLEM

Find the number of neutrons in an atom of ${}^{79}_{34}Se$.

**SOLUTION:** Identify the known and unknown values.

*Known*
atomic number = 34
mass number = 79

*Unknown*
number of neutrons = ?

**1.** Write the relationship for number of neutrons, atomic number, and atomic mass.

Neutrons = Mass number − Atomic number

**2.** Substitute the known values and solve for the number of neutrons.

Neutrons = 79 − 34 = 45

## SAMPLE PROBLEM

Atomic mass can be calculated from the mass and the abundance of naturally occurring isotopes. Carbon has two naturally occurring stable isotopes. Most carbon atoms—98.89%—are C-12, while the remaining 1.108% are C-13. What is the atomic mass of carbon?

**SOLUTION:** Identify the known and unknown values.

| *Known* | *Unknown* |
|---|---|
| 98.89% C-12 | atomic mass = ? amu |
| 1.108% C-13 | |

1. Convert the percentages to decimal numbers, and multiply the mass of each isotope by its decimal abundance.

   $12 \text{ amu} \times 0.9889 = 11.87 \text{ amu}$
   $13 \text{ amu} \times 0.01108 = 0.1440 \text{ amu}$

2. Add these masses of isotopes.

   $11.87 \text{ amu} + 0.1440 \text{ amu} = 12.01 \text{ amu}$

How can chlorine have an atomic mass of 35.454 amu? The answer is found in the relative numbers of the isotopes of chlorine. There are two major isotopes of chlorine, Cl-35 and Cl-37. The atomic mass of chlorine is the average of the two isotopes. But the average of Cl-35 and Cl-37 would seem to give chlorine an average mass of 36 amu. That would be true if Cl-35 and Cl-37 were equally abundant in nature, but such is not the case.

If you had four test grades, 90%, 90%, 90% and 80%, you would not have an average test grade of 85%. Your average would be 87.5%. In the same way, if there are many more atoms of Cl-35 than Cl-37, the average mass would be closer to 35 amu. Consult either the periodic table or a table of properties of the elements for average atomic masses.

## Location of Electrons

Remember that electrons are found in the space of the atom around the nucleus. Experiments have shown that the electrons are not found just anywhere around the nucleus; they are found in orbitals. An orbital is a region where an electron can most probably be found.

**Energy Levels** The orbitals in an atom form a series of energy levels in which electrons may be found. Each electron in an atom has its own distinct amount of energy that corresponds to the energy level that it occupies. Electrons can gain and lose energy and move to different energy levels, but they do so in a unique way. Instead of being able to absorb any amount of energy, an electron can only absorb a discrete, or fixed amount of energy that would allow it to move to a higher energy level. While this concept is difficult for us to understand, an analogy may help. When we climb up or down a set of stairs, we must exert enough energy to move from one step to another. We can't stop at a half a step. In a like manner, if an electron moves from one energy level to a different energy level, it must give off or absorb the energy difference between those two levels.

**Ground and Excited States** When the electrons occupy the lowest available orbitals, the atom is said to be in the **ground state.** The electrons in a ground state atom have filled the available spaces from the lowest energy level to higher levels until all the electrons are accounted for. The linear symbol Na-2-8-1 shows the electron arrangement for a ground state sodium atom.

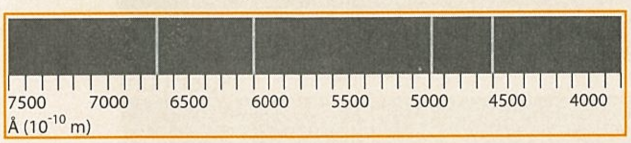
When electrons are subjected to stimuli such as heat, light, or electricity, an electron may absorb energy and temporarily move to a higher energy level. This unstable condition is called an **excited state.** Na-2-7-2 is one of the many possible arrangements for an excited atom of sodium. An excited-state electron quickly returns to a lower available level, emitting the same amount of energy it absorbed to go to the higher energy level.

The energy emitted may be in the form of infrared, ultraviolet, or visible light. The light given off from a fluorescent or a neon light is caused by excited electrons returning to lower energy levels. While the light appears as one color to our eyes, it is actually composed of many different wavelengths, each of which is seen as a different line when viewed through an instrument called a spectroscope.

Unlike a continuous spectrum produced by holding a prism in sunlight, the visible light produced by electrons is confined to narrow lines of color called bright line spectra. Each atom has its own distinct pattern of emission lines (or bright line spectrum), and these spectra are used to identify elements.

## SAMPLE PROBLEM

What element is represented by the following line spectrum?




**Bright-line spectrum of an element**

**SOLUTION:** Identify the known and unknown values.

| *Known* | *Unknown* |
|---|---|
| Spectra of several elements | Identity of the element = ? |

1. Compare the lines on the spectrum of the element shown above to those in Figure 1-6.

2. Notice that the first line shown for the unknown element is at 4600. Two elements on the reference table have spectral lines at that frequency, Li and Sr. The second line of the unknown is at 4960. Both elements have lines approximately at this reading, but Sr has two lines between 4600 and 4960 that are not in the unknown. The unknown is Li. Check for accuracy by noting that Li has a line at 6090, while Sr does not.

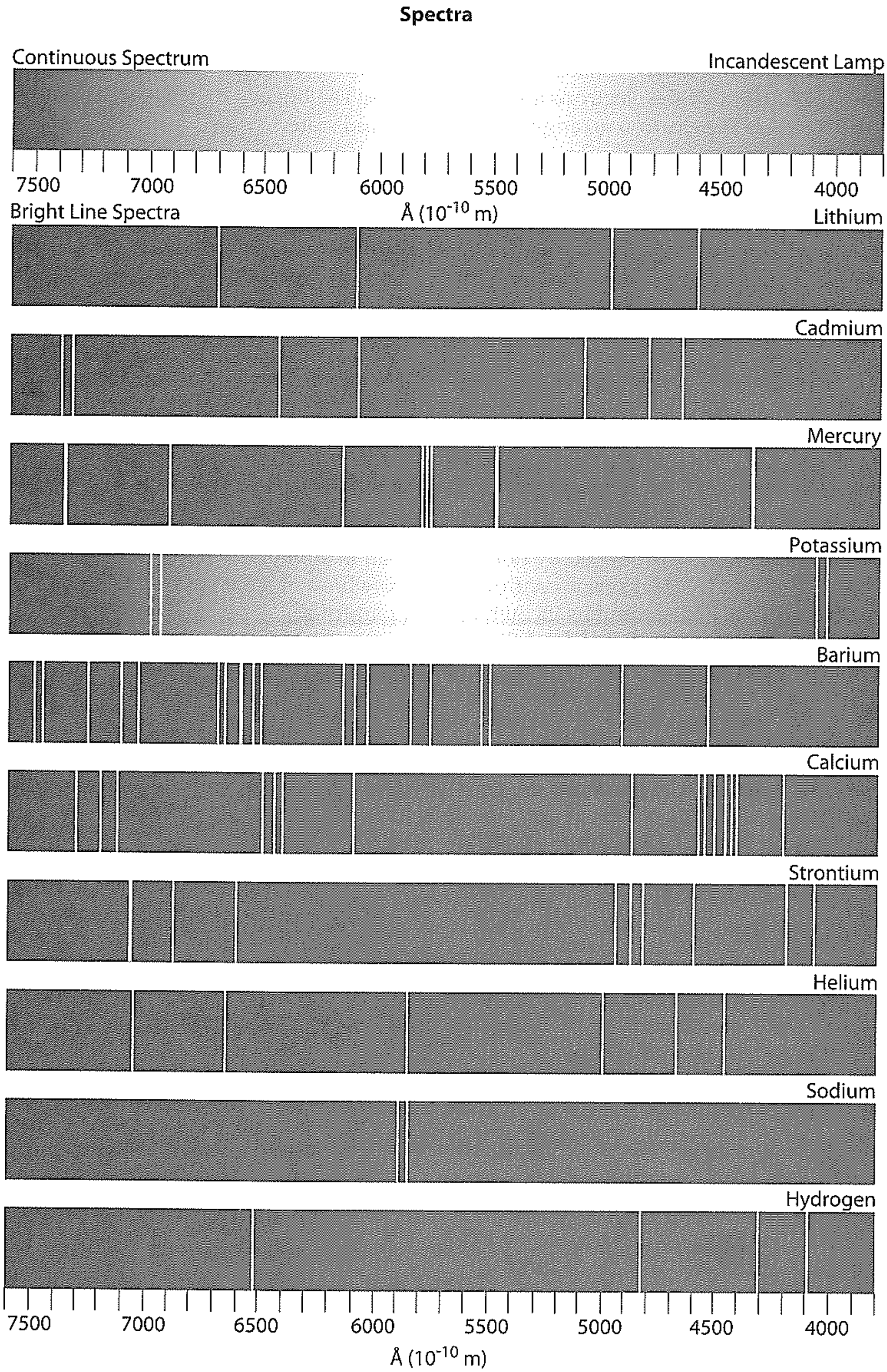



**Figure 1-6. Emission spectra:** The bright lines are emission lines and are unique to each type of atom.

## Review Questions

Set 1.2

**13.** The atomic mass of an element is defined as the weighted average mass of that element's

(1) most abundant isotope
(2) least abundant isotope
(3) naturally occurring isotopes
(4) radioactive isotopes

**14.** Element X has two isotopes. If 72.0% of the element has an isotopic mass of 84.9 amu and 28.0% has an isotopic mass of 87.0 amu, the average atomic mass of element X is numerically equal to

(1) (72.0 + 98.9)(28.0 + 87.0)
(2) (72.0 − 84.9)(28.0 − 87.0)
(3) (0.720)(84.9) + (0.280)(87.0)
(4) (72.0)(84.9) + (28.0)(87.0)

**15.** A neutral atom with 6 electrons and 8 neutrons is an isotope of

(1) carbon
(2) silicon
(3) nitrogen
(4) oxygen

**16.** The average isotopic mass of chlorine is 35.5 amu. Which mixture of isotopes (shown as percents) produces this mass?

(1) 50% C-12 and 50% C-13
(2) 50% Cl-35 and 50% Cl-37
(3) 75% Cl-35 and 25% Cl-37
(4) 75% C-12 and 25% C-13

**17.** The major portion of an atom's mass consists of

(1) electrons and protons
(2) electrons and neutrons
(3) neutrons and positrons
(4) neutrons and protons

**18.** Which atoms have the same number of neutrons?

(1) H-1 and He-3
(2) H-2 and He-4
(3) H-3 and He-3
(4) H-3 and He-4

**19.** Atoms of $^{16}O$, $^{17}O$ and $^{18}O$ have the same number of

(1) neutrons but a different number of protons
(2) protons but a different number of neutrons
(3) protons but a different number of electrons
(4) electrons but a different number of protons

**20.** A neutron has approximately the same mass as

(1) an alpha particle
(2) a beta particle
(3) an electron
(4) a proton

**21.** The total number of protons and neutrons in the nuclide $^{35}_{17}Cl$ is

(1) 52 (2) 35 (3) 18 (4) 17

**22.** The nuclides $^{14}_{6}C$ and $^{14}_{7}N$ are similar in that they both have the same

(1) mass number
(2) atomic number
(3) number of neutrons
(4) nuclear charge

**23.** What is the nuclear charge of an atom with a mass of 23 and an atomic number of 11?

(1) 11+ (2) 12+ (3) 23+ (4) 34+

**24.** Compared to the charge and mass of a proton, an electron has

(1) the same charge and a smaller mass
(2) the same charge and the same mass
(3) an opposite charge and a smaller mass
(4) an opposite charge and the same mass

**25.** Which of the following statements is correct?

(1) A proton is positively charged; a neutron is negatively charged.
(2) A proton is negatively charged; a neutron is positively charged.
(3) A proton is positively charged; an electron is negatively charged.
(4) A proton is negatively charged; an electron is positively charged.

**26.** Which symbols represent atoms that are isotopes of each other?

(1) $^{14}C$ and $^{14}N$
(2) $^{16}O$ and $^{18}O$
(3) $^{131}I$ and $^{131}I$
(4) $^{222}Rn$ and $^{222}Ra$

**27.** When electrons in an excited state fall to lower energy levels, energy is

(1) absorbed
(2) released
(3) neither absorbed nor released
(4) both released and absorbed

**28.** The characteristic bright-line spectrum of an atom is produced when

(1) nuclei undergo fission
(2) nuclei undergo fusion
(3) electrons move from higher to lower energy levels
(4) electrons move from lower to higher energy levels

## Electron Arrangement

Although the electrons in an atom contribute little to the mass of an atom, their arrangement determines its chemical properties. The chemical properties of an element are based on the number of electrons in the outer energy level of its atoms. These outer electrons are called valence electrons. How can you determine how the electrons are arranged in an atom and, therefore, how many valence electrons an atom has?

### Quantum Numbers

Remember that the first energy level in an atom can contain two electrons and the second can contain eight. We can't see the electron arrangement in an atom. How were these numbers determined? A theory, called the quantum theory, was developed to explain the chemical behavior of atoms.

Electrons can be described by a set of four numbers called quantum numbers. The first number describes the major energy level of the electron and is called the principal quantum number. The principal quantum number is the same as the number of the energy level that contains the electron. If an electron has a principal quantum number of 2, it is in the second energy level from the nucleus.

Each energy level has one or more sublevels associated with it. Each energy level contains as many sublevels as the number of the level. For example, energy level three has three sublevels.

The first sublevel of any energy level is designated the s sublevel. If a second sublevel is present, it is *p*. The third is *d*, and the fourth is *f*. Sublevels are described by using the number of the principal energy level together with the letter designation of each sublevel. For example, 3*s* describes the first sublevel of the third energy level.

The third quantum number relates to the orbitals in the sublevels and their orientations. Remember that an orbital is a location inside the atom where an electron is most likely to be found.

Electrons that are in s sublevels are found in orbitals with spherical shapes without sharp edges surrounding the nucleus. There is only one way a sphere can be arranged, so there is only one orbital in an *s* sublevel.

The *p* orbital is somewhat dumbbell in shape. There are three of these orbitals at each principal energy level higher than energy level one. The *p* orbitals are arranged at right angles to each other and can be designated as $p_x$, $p_y$, and $p_z$. Thus, each *p* sublevel contains three orbitals. Figure 1-7 shows the shapes of *s* and *p* orbitals.

At levels three and higher, there is another type of sublevel, the *d* sublevel containing five orbitals. From principal level four and higher, *f* sublevels with seven orbitals are found. The shapes of the orbitals in both the *d* and *f* sublevels are complex, so only *s* and *p* orbitals are shown.

The fourth quantum number relates to the spin of an electron. This number indicates that each orbital can contain two electrons spinning in opposite directions.

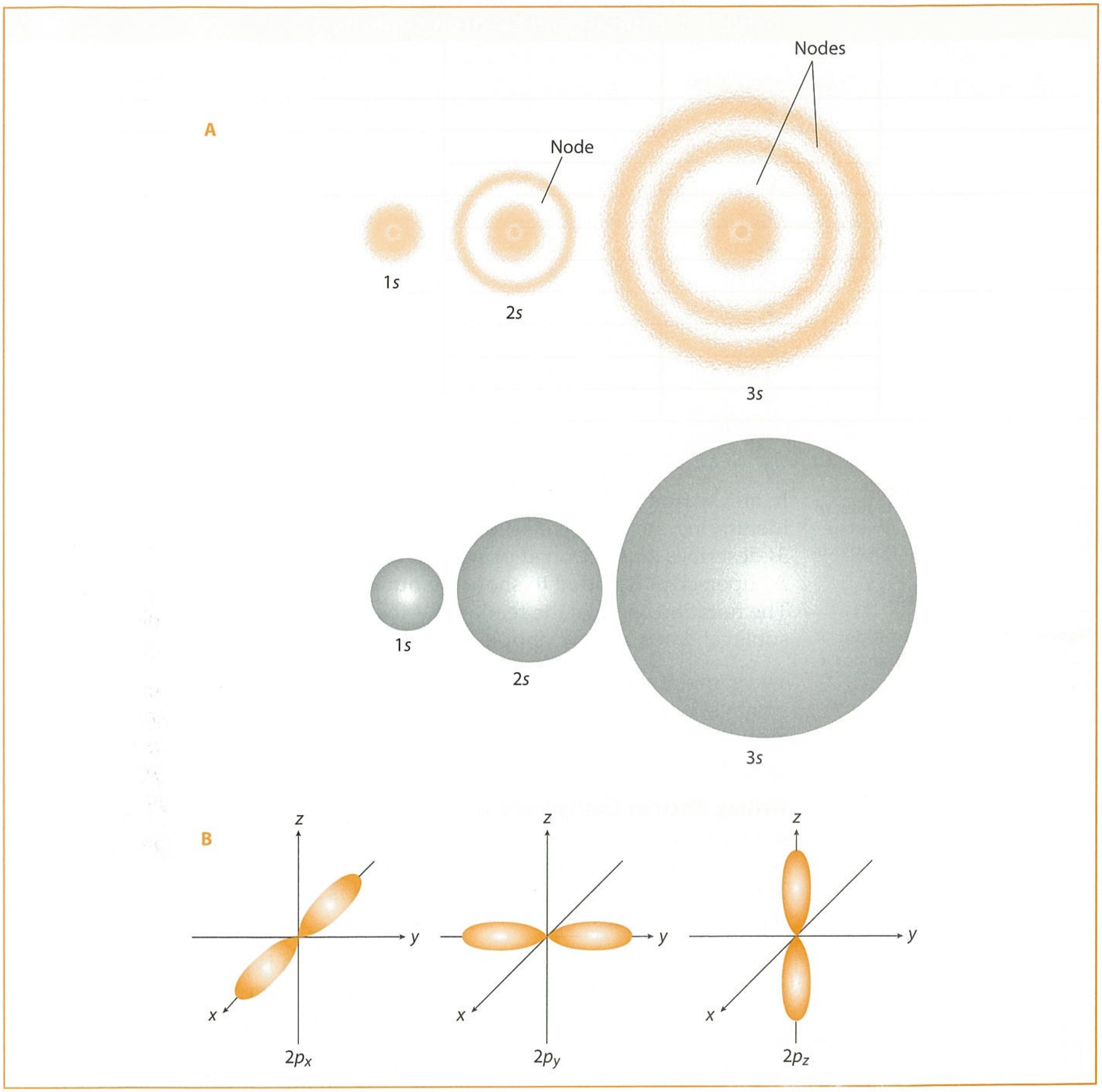



**Figure 1-7. Shape and relative sizes of orbitals: (A) Look at the shape and relative sizes of 1*s*, 2*s*, and 3*s* orbitals. The upper diagrams are cross sections of the diagrams beneath. The dark areas show where electrons are most probably located. Notice that there are areas, called nodes, where it is unlikely to find an electron. (B) Shapes and orientations of *p* orbitals**

Table 1-3 summarizes how the maximum number of electrons per energy level is determined using these four quantum numbers.

## Electron Configurations

Quantum numbers describe the distribution of the electrons in an atom when you remember that electrons will occupy the lowest sublevel possible. This distribution of the electrons in an atom is called its electron configuration.

**Table 1-3. Orbitals and Electron Capacity**

| Principal Energy Level | Type of Sublevel | Number of Orbitals in a Sublevel | Total Orbitals per Level | Maximum Number of Electrons |
|---|---|---|---|---|
| 1 | *s* | 1 | 1 | 2 |
| 2 | *s* | 1 | 4 | 8 |
| | *p* | 3 | | |
| 3 | *s* | 1 | 9 | 18 |
| | *p* | 3 | | |
| | *d* | 5 | | |
| 4 | *s* | 1 | 16 | 32 |
| | *p* | 3 | | |
| | *d* | 5 | | |
| | *f* | 7 | | |

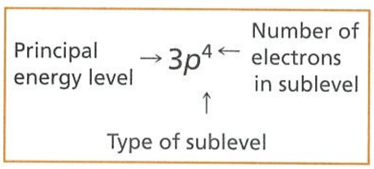



**Figure 1-8. Orbital notation:** Each part of orbital notation has a specific meaning.

In an electron configuration, the electrons of an atom are described by identifying the energy level of each electron and its sublevel. Thus, 3*s* describes an electron at principal energy level 3 in an s sublevel. A superscript is added to show the number of electrons in the sublevel. The notation $4p^5$ tells the reader that there are 5 electrons in the 4*p* sublevel. Look at the example in Figure 1-8.

The complete electron configuration of an atom is shown by writing symbols for all the occupied sublevels in sequence, starting from the orbital with the least amount of energy. For example, the electron configuration of the oxygen atom (eight electrons) is represented by $1s^2 2s^2 2p^4$.

**Writing Electron Configurations** The electron configurations of the elements can be written in order of increasing atomic number, starting with hydrogen, by adding an additional electron for each new atom. The order in which the sublevels are filled is shown in Figure 1-9, using the following rules.

- Each added electron is placed into the sublevel of lowest available energy.
- No more than two electrons can be placed in any orbital.
- A single electron must be placed into each orbital of a given sublevel before any pairing takes place. (Hund's Rule)
- The outermost principal energy level can only contain electrons in *s* and *p* orbitals.

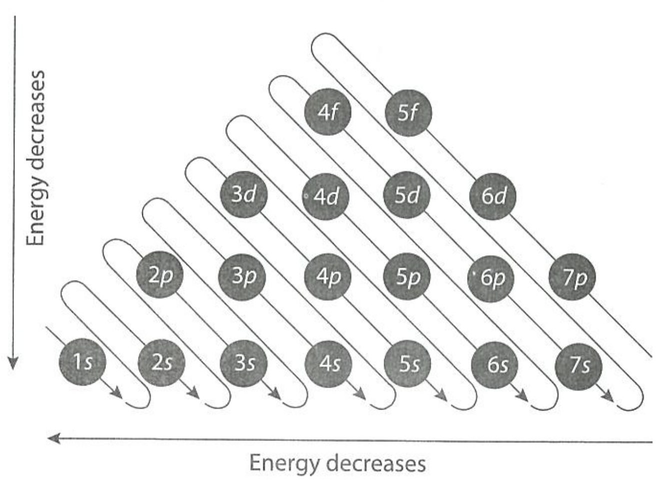



**Figure 1-9. Electron configurations:** To find the electron configuration of an atom, simply begin adding electrons to the 1*s* sublevel and continue adding them in the order shown.

**Order of Electron Fill** While there are many locations that electrons might fill in an atom, the most stable condition exists when they fill the lowest available energy orbitals. This simply means that the first energy level, which is less energetic than any other, is filled first. In level two, the *s* orbital, then the *p* orbitals, are filled. Next, the *s* and *p* orbitals of the third level are filled, but the $3d$ level is not filled next. Instead, the $4s$ sublevel is filled, followed by the $3d$. Why does this change in order occur? As the number of sublevels per energy level increases, the space taken up by the sublevels increases and the energy levels begin to overlap.

**Orbital Notation** While electron configuration notation is useful, it does not show how electrons are distributed in each sublevel. Figure 1-10 shows two ways of illustrating the distribution of electrons in an atom. A circle or square can be used to represent an orbital. An electron is represented either by a line or an arrow. When two lines are drawn in an orbital they represent an orbital pair with opposite spins. If arrows are used to represent the electrons, two arrows pointed in opposite directions represent a pair of electrons with opposite spin.

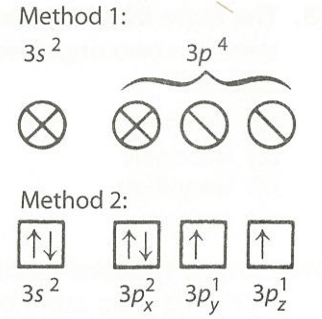



**Figure 1-10.** Two methods of showing orbital notation: The arrows in an orbital are drawn in opposite directions to indicate that the electrons have opposite spins.

## SAMPLE PROBLEM

A phosphorus atom has an electron configuration of $1s^22s^22p^63s^13p^4$. Is the atom in its ground state, or is it in an excited state?

**SOLUTION:** Identify the known and unknown values.

| *Known* | *Unknown* |
|---|---|
| electron configuration of $1s^22s^22p^63s^13p^4$ | excited or ground state |

**1.** Look at Figure 1-10 for order of filling of orbitals.

**2.** If the order is changed, or if a sublevel other than the last one is unfilled, the atom is probably in an excited state. The ground state configuration of a phosphorus atom would be $1s^22s^22p^63s^23p^3$. In the known configuration, one electron is in a higher sublevel than it would be in its ground state, so the atom is excited.

## Review Questions — Set 1.3

**29.** Which is the electron configuration of an atom in the excited state?

(1) $1s^22s^22p^2$
(2) $1s^22s^22p^1$
(3) $1s^22s^22p^53s^2$
(4) $1s^22s^22p^63s^1$

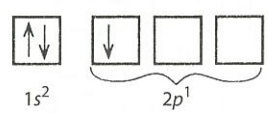
**30.** Which atom in the ground state contains only one completely filled $p$ orbital?

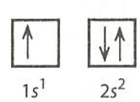
(1) Ne (3) He
(2) O (4) Be

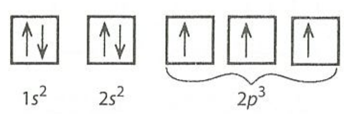
**31.** What is the total number of electrons in the second principal energy level of a calcium atom in the ground state?

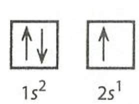
(1) 6 (3) 8
(2) 2 (4) 18

**32.** Which is the correct orbital notation of a lithium atom in the ground state?

(1)



(2)



(3)



(4)


**33.** The atom of which element in the ground state has two unpaired electrons in the 2*p* sublevel?

(1) fluorine
(2) nitrogen
(3) beryllium
(4) carbon

**34.** What is the total number of occupied *s* orbitals in an atom of nickel in the ground state?

(1) 1 (2) 2 (3) 3 (4) 4

**35.** Which atom in the ground state has only three electrons in the 3*p* sublevel?

(1) phosphorus (3) argon
(2) potassium (4) aluminum

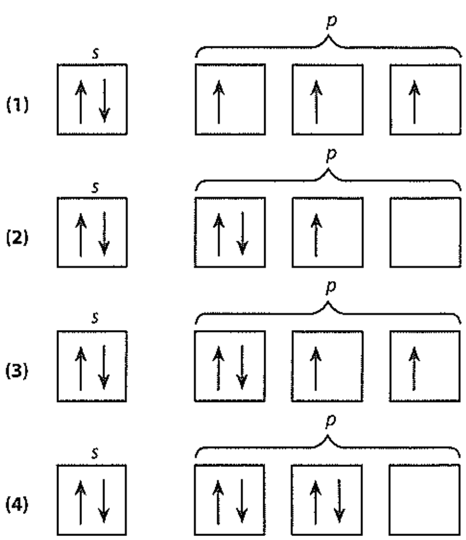
**36.** What is the total number of occupied principal energy levels in a neutral atom of neon in the ground state?

(1) 1 (2) 2 (3) 3 (4) 4

**37.** Which is the electron configuration of an atom in the excited state?

(1) $1s^12s^1$
(2) $1s^22s^1$
(3) $1s^22s^22p^1$
(4) $1s^22s^22p^2$

**38.** Which orbital notation correctly represents the outermost principal energy level of a nitrogen atom in the ground state?




**39.** Which electron configuration represents a potassium atom in the excited state?

(1) $1s^22s^22p^63s^23p^3$
(2) $1s^22s^22p^63s^13p^4$
(3) $1s^22s^22p^63s^23p^64s^1$
(4) $1s^22s^22p^63s^23p^54s^2$

**40.** In an atom of lithium in the ground state, what is the total number of orbitals that contain only one electron?

(1) 1 (2) 2 (3) 3 (4) 4

**41.** What is the total number of completely filled principal energy levels in an atom of argon in the ground state?

(1) 1 (2) 2 (3) 3 (4) 4

**42.** What is the total number of electrons needed to completely fill all the orbitals in an atom's second principal energy level?

(1) 16 (2) 2 (3) 8 (4) 4

**43.** An atom in the excited state can have an electron configuration of

(1) $1s^22s^2$
(2) $1s^22p^1$
(3) $1s^22s^22p^5$
(4) $1s^22s^22p^6$

**44.** What is the total number of sublevels in the fourth principal energy level?

(1) 1 (2) 2 (3) 3 (4) 4

**45.** Which electron configuration represents an atom in the excited state?

(1) $1s^22s^22p^63s^2$
(2) $1s^22s^22p^63s^1$
(3) $1s^22s^22p^6$
(4) $1s^22s^22p^53s^2$

**46.** Which element has atoms in the ground state with a sublevel that is only half filled?

(1) helium (3) nitrogen
(2) beryllium (4) neon

**47.** Which sublevel contains a total of five orbitals?

(1) *s* (2) *p* (3) *d* (4) *f*

**48.** What is the maximum number of electrons that can occupy the fourth principal energy level of an atom?

(1) 6 (2) 8 (3) 18 (4) 32

**49.** What is the total number of unpaired electrons in an atom of oxygen in the ground state?

(1) 6 (2) 2 (3) 8 (4) 4

**50.** Which of the following sublevels has the highest energy?

(1) 2*p* (2) 2*s* (3) 3*p* (4) 3*s*

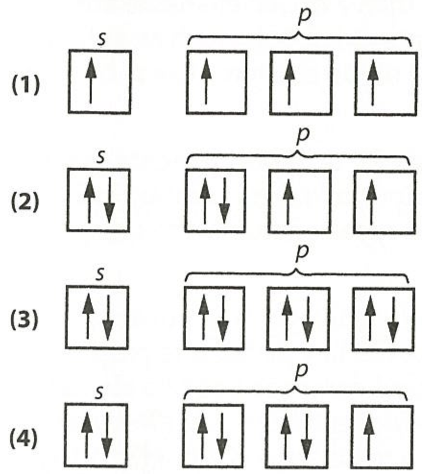
**51.** What is the maximum number of electrons in an orbital of any atom?

(1) 1 (2) 2 (3) 6 (4) 10

52. What is the electron configuration of a Mn atom in the ground state?

(1) $1s^22s^22p^63s^2$
(2) $1s^22s^22p^63s^23p^6s3d^54s^2$
(3) $1s^22s^22p^63s^23p^63d^54s^14p^1$
(4) $1s^22s^22p^63s^23p^63d^7$

53. Which orbital notation correctly represents a noble gas in the ground state?




54. Which atom in the ground state has three half-filled orbitals?

(1) P
(2) Si
(3) Al
(4) Li

55. What is the total number of completely filled sublevels found in an atom of krypton in the ground state?

(1) 10
(2) 2
(3) 8
(4) 4

56. Assuming that the orbitals of nickel fill in the order described in Figure 1-10, what is the total number of sublevels that contain electrons in the third principal energy level of a nickel atom in the ground state?

(1) 1
(2) 2
(3) 3
(4) 4

57. An atom has an electron configuration $1s^22s^22p^63s^23p^5$. How many valence electrons are represented in this configuration?.

(1) 2
(2) 3
(3) 5
(4) 7

# Types of Matter

The world is composed of millions of different materials, and they are all combinations of atoms. As we look at the world around us, two categories of matter can be distinguished.

## Homogeneous and Heterogeneous Matter

Some matter looks uniform and doesn't seem to be made up of parts. A sample of pure water does not have distinguishable parts and has the same composition throughout. When a material has uniform composition throughout, the sample is said to be **homogeneous.** Homogeneous matter can contain more than one type of particle, but particles are uniformly distributed. Sugar dissolved in water is an example of matter that contains both sugar and water but is homogeneous because the smallest particles that make up sugar and water are uniformly distributed.

Other materials are obviously made up of parts. A chocolate chip cookie has pieces of chocolate embedded in the cookie dough. When you examine a piece of concrete, you can see tiny pebbles and pieces of sand embedded in the cement. Such materials, which have varying composition, are said to be **heterogeneous.** Heterogeneous materials are made up of parts with different chemical and physical properties. These parts are not uniformly mixed or dispersed.

Matter can be divided into the major categories of pure substances and mixtures. Pure substances are homogeneous; mixtures can be either heterogeneous or homogeneous.

## Pure Substances

A sample of matter is a **pure substance** if its composition is the same throughout the sample. The two types of pure substances are elements and compounds. Oxygen gas, an element, and water, a compound, are examples of pure substances.

**Elements** **Elements** are substances that cannot be broken down or decomposed into simpler substances by chemical means. There are 91 elements that occur naturally, and more than a dozen elements are synthesized in laboratories. Most elements are metals, such as gold, iron, and aluminum. Examine a periodic table of the elements to see how many different elements you recognize.

**Compounds** **Compounds** are composed of two or more elements that are chemically combined in definite proportions by mass. Although all compounds contain at least two different types of atoms, the composition of a compound is the same throughout.

The law of definite proportions is the statement that types of atoms in a compound exist in a fixed ratio. Examine the law of definite proportions as shown in Figure 1-11. Water is a compound composed of two elements—hydrogen and oxygen—that are chemically combined. Water can be decomposed into these two elements in a mass ratio of 1:8. When any sample of water is decomposed it will always yield one part by weight of hydrogen for each eight parts of oxygen. When 9 g of water are decomposed they will always produce 1 g of hydrogen and 8 g of oxygen. If 36 g of water decomposed, how many grams of oxygen would be produced? Because the proportions remain the same, 32 g of oxygen would be produced.

Pure substances have a constant composition, both within a given sample and from one sample to another. There is another type of matter that does not have a constant composition.

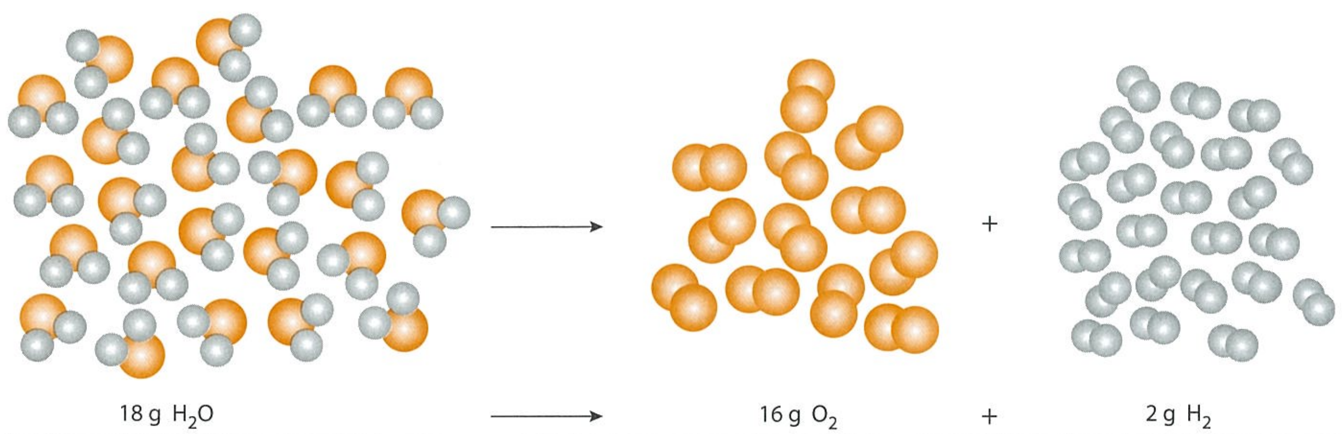



**Figure 1-11. The law of definite proportions:** This diagram is a model of the decomposition of water. Notice that for every 18 g of water, 16 g of oxygen and 2 g of hydrogen form.

## Mixtures

**Mixtures** are combinations of two or more pure substances that can be separated by physical means. Mixtures are different from compounds because their composition is not definite or "fixed," and the parts can be separated by physical means. For example, different amounts of sugar can be dissolved in a liter of water, and each result would be a water solution of sugar. Even though the sugar seems to disappear and become part of the water, it really doesn't. If the water evaporates, the sugar is left behind; the water and sugar separate.

Some mixtures are homogeneous, and some are heterogeneous. Solutions are mixtures that are homogeneous. Most mixtures are heterogeneous. Soil and concrete are good examples of heterogeneous mixtures. The different parts of each can be easily seen.

## Distinguishing Between Mixtures and Compounds

Look at Figure 1-12. Both mixtures and compounds contain two or more different elements. However, the two categories are quite different when one considers their composition and properties.

In a mixture, elements such as iron and sulfur can be present in different ratios. Each substance that makes up the mixture retains its properties. Iron is magnetic and can be separated from a mixture of iron and sulfur with a magnet. Sulfur retains its elemental yellow color in the mixture.

However, if these two elements chemically react, they combine in a mass ratio of 1.74 parts of iron to 1.00 part of sulfur. In the compound the iron is no longer magnetic, and the sulfur loses its yellow color. The compound has its own properties. For example, iron sulfide has a different melting point than either elemental sulfur or iron.

In a later topic, you will learn about different methods that can be used to separate the parts of a mixture.

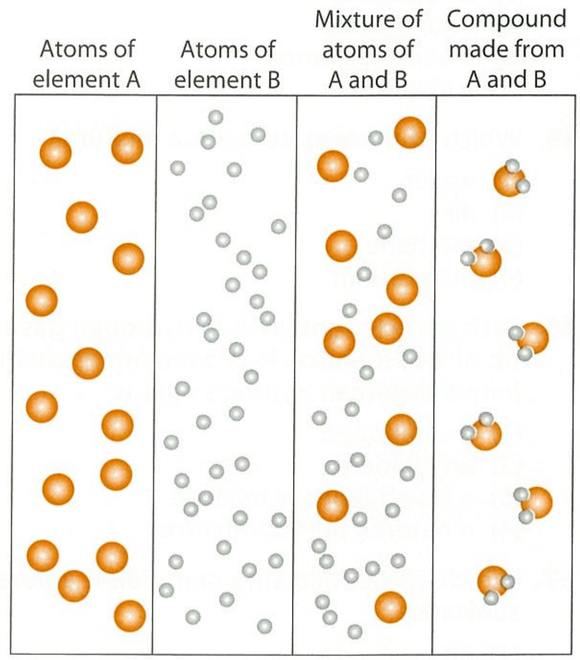



**Figure 1-12. Elements, compounds and mixtures: Study the models and notice the differences among elements, compounds, and mixtures.**

## Review Questions — Set 1.4

**58.** Which of the following cannot be decomposed by chemical means?

(1) sodium (2) ethanol (3) sucrose (4) water

**59.** A compound differs from an element in that a compound

(1) is homogeneous
(2) has a definite composition
(3) has a definite melting point
(4) can be decomposed by a chemical reaction

**60.** A compound differs from a mixture in that a compound always has a

(1) homogeneous composition
(2) maximum of two elements
(3) minimum of three elements
(4) heterogeneous composition

**61.** Most elements are

(1) metals (2) nonmetals (3) gases (4) made in a laboratory

**62.** A pure substance that is composed only of identical atoms is classified as

(1) a compound
(2) an element
(3) a heterogeneous mixture
(4) a homogeneous mixture

**63.** Which is characteristic of all mixtures?

(1) They are homogeneous.
(2) They are heterogeneous.
(3) Their compositions are in a definite ratio.
(4) Their compositions may vary.

**64.** A heterogeneous material may be

(1) an element
(2) a compound
(3) a pure substance
(4) a mixture

**65.** Which of these materials is a mixture?

(1) water
(2) air
(3) methane
(4) magnesium

**66.** Each particle contained in hydrogen gas is made up of two identical hydrogen atoms chemically joined together. Hydrogen gas is

(1) a compound
(2) an element
(3) a homogeneous mixture
(4) a heterogeneous mixture

**67.** Which of the following materials is a pure substance?

(1) air
(2) water
(3) fire
(4) earth

**68.** Which statement is an identifying characteristic of a mixture?

(1) A mixture can consist of a single element.
(2) A mixture can be separated by physical means.
(3) A mixture must have a definite composition by weight.
(4) A mixture must be homogeneous.

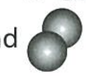
**69.** Which substance can be decomposed by a chemical change?

(1) ammonia
(2) aluminum
(3) magnesium
(4) manganese

**Answer the following questions using complete sentences.**

**70.** A sample of a material is passed through a filter paper. A white deposit remains on the paper, and a clear liquid passes through. The clear liquid is then evaporated, leaving a white residue. What can you determine about the nature of the sample?

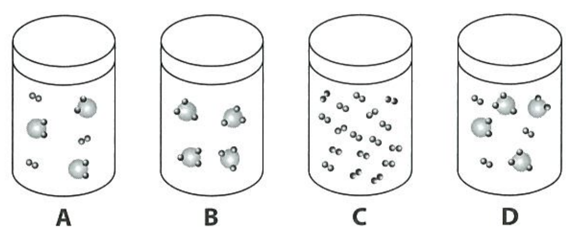
**71.** A substance is found to contain only calcium and sulfur. How would you determine whether the substance is a compound or a mixture?

**72.** Using  to represent a hydrogen molecule and  to represent an oxygen molecule, draw a picture of a mixture of hydrogen and oxygen gases.

**73.** What are some of the differences between a mixture of iron and oxygen and a compound composed of iron and oxygen?

**74.** Is a pepperoni pizza homogeneous or heterogeneous? Explain your answer.

**75.** Examine the contents of the four containers shown below. Use complete sentences to identify each as containing only elements, only compounds or a mixture of these. Explain each of your answers.




**76.** Are the contents of Container D in question 75 homogeneous or heterogeneous? Explain your answer.

**77.** A chemist receives two samples. Analysis of one sample shows it to be 88.88% oxygen by mass and 11.12% hydrogen. Analysis of the other sample shows it to be 94.12% oxygen and 5.88% hydrogen. Are these samples of the same material? Explain your answer.

# Practice Questions for the New York Regents Exam

TOPIC 1

**Directions**
Review the Test-Taking Strategies section of this book. Then answer the following questions. Read each question carefully and answer with a correct choice or response.

## Part A

1 The model of the atom that pictured the atom with electrons traveling in circular orbits was called the
(1) planetary model
(2) cannonball model
(3) wave-mechanical model
(4) plum pudding model

2 Which sequence represents a correct order of historical developments leading to the modern model of the atom?
(1) the atom is a hard sphere → most of the atom is empty space → electrons exist in orbitals outside the nucleus
(2) the atom is a hard sphere → electrons exist in orbitals outside the nucleus → most of the atom is empty space
(3) most of the atom is empty space → electrons exist in orbitals outside the nucleus → the atom is a hard sphere
(4) most of the atom is empty space → the atom is a hard sphere → electrons exist in orbitals outside the nucleus

3 Compared to the entire atom, the nucleus of the atom is
(1) smaller and contains most of the atom's mass
(2) smaller and contains little of the atom's mass
(3) large and contains most of the atom's mass
(4) large and contains little of the atom's mass

4 In a famous experiment, positively charged particles were aimed at a thin sheet of gold foil. The results of this experiment were that
(1) most of the particles failed to pass through the foil
(2) most of the particles were repelled, showing that gold has a negative core
(3) a few of the particles were repelled, showing that the gold has a positive core
(4) a few of the particles were repelled, showing that the gold was neutral

5 Neutral atoms must contain equal numbers of
(1) protons and electrons
(2) protons and neutrons
(3) protons, neutrons, and electrons
(4) neutrons and electrons

6 Which of the following is true of a compound but not a mixture?
(1) A compound contains more than one element.
(2) All the nuclei in a compound contain the same number of protons.
(3) A compound may be heterogeneous.
(4) The composition of a compound does not vary.

7 Compared with an electron, a proton has
(1) more mass and the same charge
(2) more mass and an opposite charge
(3) equal mass and the same charge
(4) equal mass and an opposite charge

8 The total number of electrons in a neutral atom of any element is always equal to the atom's
(1) mass number
(2) number of neutrons
(3) number of protons
(4) number of nucleons

9 All isotopes of neutral atoms of sodium have
(1) 11 protons and 12 neutrons
(2) 12 protons and 11 neutrons
(3) 11 protons and 11 electrons
(4) 12 protons and 12 electrons

10 There are three isotopes of hydrogen, H-1, H-2, and H-3. All of these isotopes have
(1) a mass of 2 amu
(2) an atomic number of 1
(3) 1, 2, or 3 neutrons
(4) 1, 2, or 3 protons

11 An atom in the excited state contains
(1) more electrons than an atom in the ground state
(2) more protons than an atom in the ground state
(3) more potential energy than an atom in the ground state
(4) more mass than an atom in the ground state

12 As an electron moves from the excited state to the ground state, the potential energy of the electron
(1) decreases
(2) increases
(3) remains the same
(4) becomes zero

13 Which of the following particles has the smallest mass?
(1) neutron
(2) electron
(3) proton
(4) hydrogen atom

14 An element occurs as a mixture of isotopes. The atomic mass of the element is based upon
(1) the mass of the individual isotopes, only
(2) the relative abundances of the isotopes, only
(3) both the masses and the relative abundances of the individual isotopes
(4) neither the masses nor the relative abundances of the individual isotopes

## Part B–1

15 100 g of a clear liquid is evaporated and a few grams of white crystals remain. The original liquid was a
(1) heterogeneous compound
(2) heterogeneous mixture
(3) homogeneous compound
(4) homogeneous mixture

16 Two samples of bronze, a uniform material, are analyzed and found to contain different percentages of tin. Based on this information, bronze is likely a
(1) homogeneous compound
(2) heterogeneous compound
(3) homogeneous mixture
(4) heterogeneous mixture

17 In the electron cloud model of the atom, an orbital is defined as the most probable
(1) location of an electron.
(2) charge of an electron.
(3) conductivity of an electron.
(4) mass of an electron.

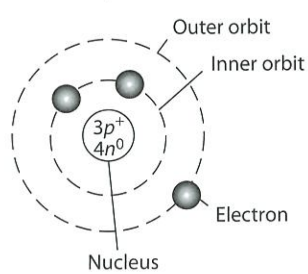
18 There are three isotopes of oxygen: O-16, O-17, and O-18. These neutral atoms contain
(1) equal numbers of protons, neutrons, and electrons
(2) equal numbers of protons and neutrons, but different numbers of electrons
(3) equal numbers of protons and electrons, but different numbers of neutrons
(4) different numbers of protons, neutrons, and electrons

19 What is the charge on a particle that contains 9 protons, 10 neutrons, and 9 electrons?
(1) It is neutral.
(2) It has a net charge of 1+.
(3) It has a net charge of 1−.
(4) It has a net charge of 28+.

20 An element has two isotopes. 90% of the isotopes have a mass number of 20 amu, while 10% have a mass number of 22 amu. The atomic mass of the element
(1) cannot be determined without knowing the atomic number
(2) is 21 amu
(3) is closer to 20 amu than to 22 amu
(4) is closer to 22 amu than to 20 amu

21 If the atomic number of a neutral element is 35, and its nucleus contains 40 neutrons, which of the following is correct?
(1) The atom is bromine, and it has 35 electrons.
(2) The atom is bromine, and it has a mass number of 40.
(3) The atom is zirconium, and it has a mass number of 75.
(4) The atom is zirconium, and it has 40 electrons.

22 Examine the diagram of the atom. What element does it represent?




(1) hydrogen
(2) helium
(3) lithium
(4) carbon

23 An atom of Cl-35 contains
(1) 17 protons, 17 neutrons, and 18 electrons
(2) 17 protons, 18 neutrons, and 17 electrons
(3) 18 protons, 17 neutrons, and 17 electrons
(4) 18 protons, 18 neutrons, and 18 electrons

24 Which must be a mixture of substances?
(1) solid
(2) liquid
(3) gas
(4) solution

25 What is the number of electrons in a completely filled second shell of an atom?
(1) 32
(2) 2
(3) 18
(4) 8

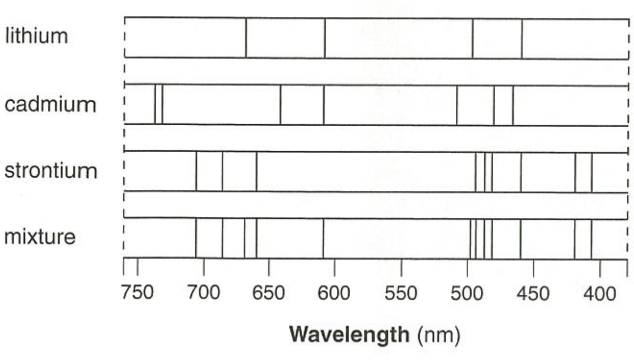
## Parts B–2 and C

26 Explain, in terms of protons and neutrons, why U-235 and U-238 are different isotopes of the element uranium.

**Base your answers to questions 27–29 on the information below.**

The bright-line spectra for three elements and a mixture of elements are shown below.

**Bright-Line Spectra**



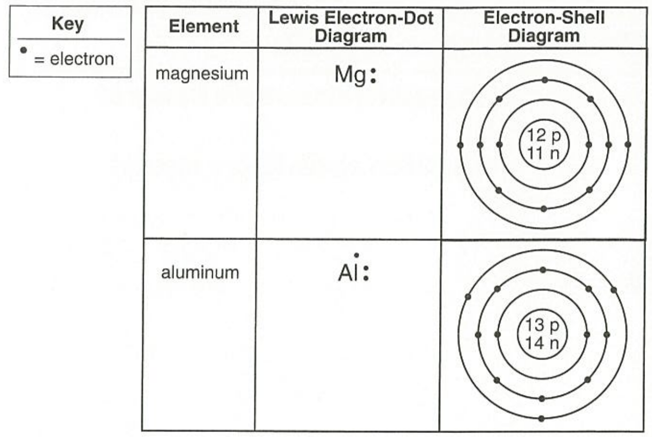

27 Explain, in terms of *both* electrons and energy, how the bright line spectrum of an element is produced.

28 Identify *all* the elements in the mixture.

29 State the total number of electrons that would be found in a neutral atom of cadmium.

**Base your answers to questions 30–32 on the information below.**

**Atomic Diagrams of Magnesium and Aluminum**




30 Explain, in terms of protons and electrons, why both of these diagrams depict atoms that are considered neutral.

31 Determine the mass number of the magnesium atom represented by the electron-shell diagram.

32 The linear symbol for the ground-state electron configuration of aluminum is Al-2-8-3. Construct a linear symbol for an excited-state configuration of the aluminum atom.

**Base your answers to questions 33 through 35 on the data table, which shows three isotopes of neon.**

**Some Isotopes of Neon**

| Isotope | Atomic Mass (atomic mass units) | Percent Natural Abundance |
|---|---|---|
| Ne-20 | 19.99 | 90.9% |
| Ne-21 | 20.99 | 0.3% |
| Ne-22 | 21.99 | 8.8% |

33 In terms of atomic particles, state one difference between these three isotopes of neon.

34 Based on the atomic masses and the natural abundances shown in the data table, show a correct numerical setup for calculating the average atomic mass of neon.

35 Based on the natural abundances, the average atomic mass of neon is closest to which whole number?

**Base your answers to questions 36 and 37 on the information below.**

Naturally occurring elemental carbon is a mixture of isotopes. The percent composition of the two most abundant isotopes is listed below.

- 98.93% of the carbon atoms have a mass of 12.00 amu.
- 1.07% of the carbon atoms have a mass of 13.00 amu.

**36** Show a correct numerical setup for calculating the average atomic mass of carbon.

**37** Describe, in terms of subatomic particles found in the nucleus, one difference and one similarity in the nuclei of the two isotopes. The response must include both isotopes.