that the rad is a *smaller* unit of dose than the gray, hence to describe a given dose in rads, one requires a *larger* numerical value. Mistakes can often be avoided by asking if the answer seems reasonable. If the new unit is smaller, a larger number is required to describe a given quantity and vice versa.

Example 1-4. A patient is given an x ray exposure X, of 5.16×10^{-5} coulombs per kg. Convert this exposure into roentgens (R), given that $1R = 2.58 \times 10^{-4}$ coulombs per kg.

In equations and in conversion factors, rather than use "per," it is simpler and better to use a fraction or a reciprocal:

$$X = 5.16 \times 10^{-5} \frac{C}{kg} \quad \text{or} \quad X = 5.16 \times 10^{-5}\ C\ kg^{-1}$$

$$1\ R = 2.58 \times 10^{-4}\ C\ kg^{-1} \quad \text{or} \quad 1\ C\ kg^{-1} = \frac{1\ R}{2.58 \times 10^{-4}}$$

Replacing $1\ C\ kg^{-1}$ by its equivalent

$$X = 5.16 \times 10^{-5}\ C\ kg^{-1}$$

$$= 5.16 \times 10^{-5} \times \frac{1\ R}{2.58 \times 10^{-4}} = .200\ R$$

By carrying the units along with the numbers we obtain our answer with its units. We then ask, is the answer reasonable? In this case, the roentgen is a much smaller unit than the C/kg, hence our answer must be a much larger number (0.2) than the original number of 5.16×10^{-5}.

1.03 ATOMS

All matter is composed of atoms. Each atom consists of a small dense nucleus with a radius of about 10^{-14}m, and a surrounding "cloud" of moving planetary electrons that travel in orbits with radii of about 10^{-10} m. The electrons have a small mass compared to the nucleus but, because of their diffuse nature, occupy a great deal of space. A group of atoms then consists of a few dense spots (nuclei) while the rest of the space occupied by the electrons is virtually empty. As an illustration, if an atom were increased in size to "occupy" a room, the nucleus would occupy a space the size of a pin point placed at the center of the room. Because of this emptiness of so-called solid matter, a high energy electron or nucleus from one atom may readily penetrate many atoms before a collision results between the moving particle and any part of the atom.

Atoms differ from one another in the constitution of their nuclei and in the number and arrangement of their electrons. *The number of electrons in the atom is referred to as the atomic number and is represented by Z.* Z ranges from one for the simplest atom (hydrogen) to 105 for the most complex atom as yet discovered (hahnium). The chemical properties of an atom are determined by the atomic number. The properties of the lighter atomic species are given in Table 1-3. The first column gives the element, the second column the symbol used to represent this element, and the third column the atomic number, Z. To understand the rest of the table, we must inquire into the structure of the nucleus.

TABLE 1-3
Atomic Numbers, Atomic Weights, and Mass Numbers of a Few of the Lighter Elements

Element	Symbol	Atomic Number (Z)	Atomic Weight (amu)	Mass Numbers of Stable Isotopes (A)	Mass Numbers of Unstable Isotopes (A)
Hydrogen	H	1	1.00797	1, 2	3
Helium	He	2	4.0026	3, 4	5, 6, 8
Lithium	Li	3	6.941	6, 7	5, 8, 9, 11
Beryllium	Be	4	9.0122	9	6, 7, 8, 10, 11, 12
Boron	B	5	10.811	10, 11	8, 9, 12, 13
Carbon	C	6	12.011	12, 13	9, 10, 11, 14, 15, 16
Nitrogen	N	7	14.0067	14, 15	12, 13, 16, 17, 18
Oxygen	O	8	15.9999	16, 17, 18	13, 14, 15, 19, 20

1.04 THE NUCLEUS

A nucleus can be broken up into its constituent parts by bombarding with high speed particles. When this occurs, it becomes evident that there are two important, fundamental particles within the nucleus: *protons and neutrons.* Either particle may be referred to as a *nucleon.* Protons carry a positive charge, equal in size but opposite in sign to that carried by the electrons, while neutrons have no charge. Protons and neutrons have nearly the same mass, some 1900 times that of the electron. Since the atom as a whole is electrically neutral, there must be one proton in the nucleus for every electron outside the nucleus. Hence Z, which represents the number of electrons outside the nucleus, also represents the number of protons in the nucleus.

Mass Number, A: The total number of nucleons in the nucleus (protons plus neutrons) is called the mass number and range from 1 for hydrogen to about 250 for the heaviest nuclei. Since Z represents the number of protons in the nucleus, (A − Z) gives the number of neutrons.

Isotopes: Most elements consist of a mixture of several atomic species with the *same* extranuclear structure but *different* nuclear masses, that is, different mass numbers. *Atoms composed of nuclei with the same number of protons but different number of neutrons are called isotopes.* Isotopes may be stable or unstable and a few of both types are given in Table 1-3. For example, hydrogen has two stable isotopes with mass numbers 1 and 2, and an unstable one with mass number 3. Helium has two stable isotopes, mass numbers 3 and 4, and three unstable isotopes, mass numbers 5, 6, and 8. Lithium consists of two stable isotopes, mass numbers 6 and 7, and four unstable isotopes, mass numbers 5, 8, 9, and 11. The stability of an isotope depends upon there being the right mixture of protons and neutrons. If there is an unbalance in this mixture, a particle will be ejected; this process will continue until a stable configuration is achieved. The ejection of a particle is called a disintegration and the isotope is said to be radioactive. This will be dealt with in later sections of this book.

Since *isotopes* have the same number of protons, and hence the same number of electrons, they *have the same chemical properties.* For this reason they cannot be separated chemically. They can, however, be separated in the mass spectrometer, which exploits the mass differences between the nuclei.

Atomic masses are related to the mass of one of the isotopes of carbon (mass number 12), which is arbitrarily assigned the value 12.0000. Since carbon 12 has 6 protons and 6 neutrons, and since protons and neutrons have nearly the same mass, each particle on this scale has a mass of nearly 1. This means that atomic masses are very nearly whole numbers and equal to the mass number. For example, the two isotopes of hydrogen have atomic masses of 1.007825 and 2.014102, which are very nearly equal to the mass numbers 1 and 2.

Atomic masses as used in chemistry (and usually called atomic weights) and represented by A are generally different from atomic masses since usually there are a number of isotopes involved in a naturally occurring element. For example, boron as found in nature consists of a mixture of two isotopes of mass numbers 10 and 11 in the proportions 19.8% and 80.2%, giving an atomic weight of 10.811 (see Table 1-3). Sometimes atomic masses are nearly whole numbers because one of the isotopes may be much more abundant than any of the others. For example, hydrogen in nature exists as a mixture of mass number 1 (99.985%) and mass number 2 (0.015%), giving an atomic mass of nearly 1 (1.00797).

NOTATION FOR ATOMIC SPECIES: It is usual to represent atomic species using subscripts and superscripts preceding the chemical symbol. For example, the three isotopes of hydrogen (see Table 1-4) are represented by ${}^{1}_{1}H$, ${}^{2}_{1}H$, and ${}^{3}_{1}H$. The subscript gives Z, the number of protons in the nucleus, while the superscript gives the mass number, A. There is some redundancy in this notation, the subscript really being unnecessary because the chemical symbol tells the chemist the atomic number. Often then one could refer to the isotopes of hydrogen as simply ${}^{1}H$, ${}^{2}H$, and ${}^{3}H$. In speaking, these are referred to as hydrogen 1, hydrogen 2, and hydrogen 3.

ISOTOPES OF HYDROGEN: The nucleus ${}^{2}H$, containing one proton and one neutron, is important in nuclear disintegration experiments. It is called a *deuteron.* An atom composed of one deuteron and an electron is

TABLE 1-4
Isotopes of Hydrogen and Helium

Element	Symbol	Number Protons	Number Neutrons	Mass Number (A)	Properties	Name of Nucleus	Name of Corresponding Atom
Hydrogen Z = 1	^1_1H	1	0	1	Stable	Proton	Hydrogen
	^2_1H	1	1	2	Stable	Deuteron	Deuterium
	^3_1H	1	2	3	Radioactive		Tritium
Helium Z = 2	^3_2He	2	1	3	Stable		
	^4_2He	2	2	4	Stable	Alpha	
	^5_2He	2	3	5	Radioactive		
	^6_2He	2	4	6	Radioactive		
	^8_2He	2	6	8	Radioactive		

called heavy hydrogen or deuterium. The nucleus ^3H, consisting of one proton and two neutrons, is radioactive and decays into an isotope of helium (^3_2He). The atom formed from ^3H is called *tritium*.

ISOTOPES OF HELIUM: There are five known isotopes of helium, ^3_2He, ^4_2He, ^5_2He, ^6_2He, and ^8_2He, of which the first two are stable and the latter three radioactive. ^4_2He is the major constituent of helium and is widely used in nuclear disintegration experiments. It is known as an *alpha* particle. Helium 5, 6, and 8 decay into isotopes of lithium.

ISOTOPES OF COBALT: ($^{54}_{27}Co$, $^{55}_{27}Co$, $^{56}_{27}Co$, $^{57}_{27}Co$, $^{58}_{27}Co$, $^{59}_{27}Co$, $^{60}_{27}Co$, $^{61}_{27}Co$, $^{62}_{27}Co$, $^{63}_{27}Co$, $^{64}_{27}Co$.) $^{59}_{27}Co$ is the only stable isotope of cobalt, containing 27 protons and 32 neutrons. The others disintegrate in a variety of ways to form isotopes of iron and nickel. Cobalt 60 is used as the source of radiation in many therapy units.

In general, as the atomic number is increased, the number of isotopes and the number of stable isotopes increase. For example, naturally occurring tin consists of a mixture of 10 stable isotopes and at least 15 radioactive ones may be produced artificially.

1.05 ELEMENTAL PARTICLES

In the last section, we saw that the nucleus consists of protons and neutrons. However, in nuclear disintegration experiments, a host of other "particles" have been discovered. A few of these of interest to us are briefly described in Table 1-5. In this table masses are expressed in terms of the mass of one of the isotopes of carbon = 12.0000, and charges in terms of the charge on the proton = 1.602×10^{-19} C.

1.06 EXTRANUCLEAR STRUCTURE

In discussing x rays and their effects on atoms, we are interested in their extranuclear structure, that is, the arrangement of the planetary electrons outside the nucleus.

TABLE 1-5
Properties of the Important Elemental Particles
(Masses given in atomic mass units, charges in terms of the charge on the proton)

Particle	Mass	Charge	Properties
proton p	1.007277	+1	The *proton* is the nucleus of the hydrogen atom. The hydrogen atom consists of 1 proton in the nucleus and 1 external electron. The mass of the neutral atom is 1.007277 + 0.000548 = 1.007825 mass units. The proton is one of the fundamental building blocks of all nuclei. Beams of protons are being used in radiotherapy.
neutron n	1.008665	0	The *neutron* is the other fundamental building block of all nuclei. Neutrons have nearly the same mass as protons. Since the neutron is an uncharged particle it is hard to stop and difficult to detect. Beams of neutrons are being used in radiotherapy.
electron e, e^- or β^-	0.000548	−1	The *electron* has a very small mass compared with the proton. Electrons abound in nature. Every atom contains electrons outside the nucleus. The electron is easily detected. It is sometimes called a negatron or beta particle and represented by e, e^-, or β^-. Beams of high energy electrons are extensively used in radiotherapy.
positron e^+ or β^+	0.000548	+1	The *positron* has the same mass as an electron but carries a positive charge. Positrons exist in nature only while they are in motion. A slowly moving or stationary positron quickly combines with an electron to form a burst of radiation in the form of two gamma rays (see below). Positrons are represented by e^+ or β^+ and referred to as beta plus particles. They are used in nuclear medicine.
photon $h\nu$ or gamma ray γ	0	0	Strictly speaking, the *photon* is not a particle, but a bundle of energy which travels at the speed of light (3×10^8 m s^{-1}). In many interactions it acts much like a particle. Photons are referred to almost interchangeably as *quanta* or *gamma rays* and are represented symbolically by $h\nu$ or γ. Beams of photons account for the major part of external beam radiotherapy.
neutrino ν_e	less than 1/8000 of an electron mass	0	The *neutrino* is a very small particle with practically no mass and no charge. For this reason, it has been very difficult to detect experimentally. Its interaction with protons to form neutrons and positrons according to the reaction $\nu_e + p \longrightarrow n + \beta^+$ has been observed. The neutrino was introduced originally from theoretical considerations to help explain beta decay.
Mu mesons μ^+ μ^-	$207m_0$ $207m_0$	+1 −1	Mu mesons may be either positively or negatively charged and have a mass 207 times the mass of the electron. They are produced indirectly by the interaction of very high energy particles with matter. The particles are unstable and decay spontaneously into electrons and neutrinos according to the reactions $\mu^+ \longrightarrow e^+ + 2\nu$, $\mu^- \longrightarrow e^- + 2\nu$. The mean life of the particles is 2.15×10^{-6} sec.

TABLE 1-5—cont'd.
Properties of the Important Elemental Particles
(Masses given in atomic mass units, charges in terms of the charge on the proton)

Particle	Mass	Charge	Properties
Pi mesons			Pi mesons may have a positive or a negative charge or may be neutral. They are produced by the bombardment of matter with high energy protons or photons. The charged π mesons decay into mu mesons and neutrinos according to $\pi^+ \longrightarrow \mu^+ + \nu$, $\pi^- \longrightarrow \mu^- + \nu$ with a mean life of 2.5×10^{-8} s. The neutral π^0 meson decays into 2 photons $\pi^0 \longrightarrow h\nu_1 + h\nu_2$ with a mean life of 10^{-15} seconds. Beams of negative π mesons are being used in radiotherapy.
π^+	$273m_0$	+1	
π^-	$273m_0$	−1	
π^0	$265m_0$	0	

Hydrogen is the simplest atom, consisting of one electron moving about the nucleus (Fig. 1-1). The nucleus, with its positive charge, attracts the electron with its negative charge, constraining it to move in an orbit much the same as the earth moves about the sun. All isotopes of hydrogen have this simple arrangement of one external electron, regardless of the number of particles in the nucleus. Helium, the next simplest atom, has two electrons. These two electrons travel in the same orbit spinning in opposite directions (Fig. 1-1). This electronic configuration is very stable and, as a result, it is impossible to make helium interact chemically with any other material. Hydrogen owes its chemical activity to the fact that it would like to acquire one more electron to achieve the dynamic stability of helium.

Lithium has 3 electrons (Fig. 1-1). The third electron must be added to a new orbit outside the first one, because 2 electrons in the inner orbit completely fill this orbit or shell. The innermost orbit or shell is referred to as the K shell. The next shells are, in order, the L, M, and N shells. Since lithium has 3 electrons, the third electron is located alone in the L

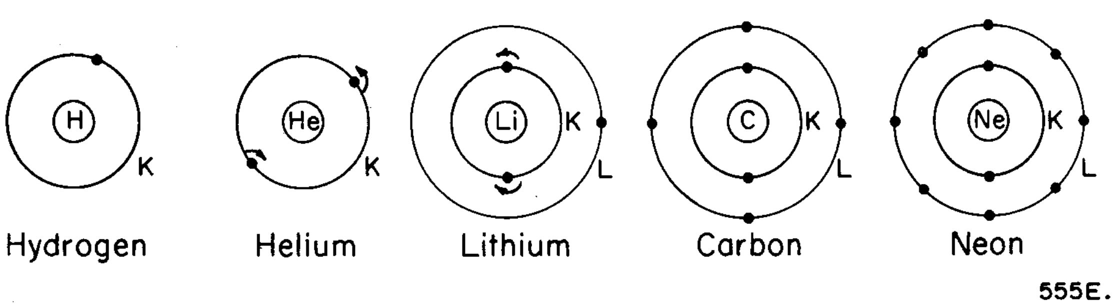

Figure 1-1. Schematic diagram showing electron structure for hydrogen, helium, lithium, carbon, and neon.

shell, a fact that makes lithium very active chemically. Generally speaking, an atom has its greatest stability if its outermost shell is completely filled. If it is not filled, it will tend to react with any element that can supply the extra electron; or if it has an excess of electrons, it will react with any element that can take these excess electrons.

As one proceeds to higher values of Z in the periodic table, the L shell gradually fills up to form beryllium (Z = 4) with 2 electrons in the L shell, then boron (Z = 5) with 3 electrons, carbon (Z = 6) with 4, nitrogen (Z = 7) with 5, oxygen (Z = 8) with 6, fluorine (Z = 9) with 7, and finally neon (Z = 10) with 8. The L shell will not hold any more electrons.

Neon, with a completely filled outer shell, is an inert gas and cannot be made to react chemically. Carbon, on the other hand, can form many compounds since it can give up 4 electrons or take on 4 electrons to achieve stability. Oxygen is 2 electrons short of a completed shell. It will try to acquire 2 electrons. Carbon and oxygen can combine to form CO_2, in which case the carbon shares its 4 outer electrons with 2 oxygen atoms. Fluorine, with 1 electron short of a completed shell, is very active. Sodium (Z = 11) is formed with the K and L shells filled and 1 electron in the M shell. Sodium will thus react with any atom, such as fluorine, that will take up one electron to form a stable compound. Chlorine is similar in structure to fluorine with one empty place in the M shell and combines with sodium to form NaCl or salt.

With increase in the atomic number, Z, the extranuclear structure becomes more and more complicated; the M shell will be filled, then the N and so on. Chemical properties will repeat themselves as the shells fill up. For example, the inert gases (helium, neon, argon, krypton, to name a few) will occur as each shell is filled. In a similar way alkaline elements (lithium, sodium, potassium) will appear when the outermost shell is occupied by only 1 electron. In general, the chemical properties and valence will be determined by the number of electrons in the outermost incompleted shell.

1.07 ATOMIC ENERGY LEVELS

Although the electrons of Figure 1-1 are shown circulating and spinning in specific orbits, we know from quantum mechanical reasoning that the electron has a finite probability of being anywhere in space, but with its most probable value near the orbit. This means orbits have no real existence. A quantity that does have real existence, however, is the energy of the atom. The atom may exist in a number of discrete energy states or energy levels, which may be measured with great precision. A few of these for tungsten are represented by the horizontal lines of Figure 1-2. The corresponding orbits are shown on the left side of Figure 1-2. The energy levels for K, L, and M shells are about 70,000 eV, 11,000 eV, and