1

ATOMIC AND NUCLEAR STRUCTURES

INTRODUCTION

This chapter introduces a number of terms and concepts that are fundamental to the understanding of the scientific basis of nuclear medicine. These terms and concepts will be repeatedly used throughout the text, such as in the description of radioactive decay, interaction between radiation and matter, dosimetry, and the operational principles of various radiation detection and imaging instruments. To ensure the reader's understanding of the differences between similar terms, the definition of some similar sounding terms is summarized in a table at the end of the chapter for easy reference (Table 1-2).

STRUCTURE OF MATTER

Material substances in the universe can be classified either as **elements** or as **compounds**. An element is a single substance which cannot be broken into simpler substances by ordinary chemical means. A compound is composed of two or more elements bound together by chemical bonds. Thus, oxygen and copper are elements, whereas water and ammonia are compounds. The smallest particle of a compound is called a **molecule** and the smallest particle of an element is called an **atom**. A molecule is made up of two or more atoms.

The atom has its own substructure. It consists of a massive, positively charged core called a **nucleus** and a cloud of negatively charged particles called **electrons** that swarm around the nucleus. The nucleus itself is made of two kinds of particles: positively charged **protons** and slightly heavier but electrically neutral **neutrons.** There are many more elementary particles found in the nucleus (quarks, for example), but they are not important to nuclear medicine. We therefore confine our attention to the three elementary particles (protons, neutrons, and electrons).

Elementary Particles

Electrons are negatively charged particles. The amount of electrical charge carried by an electron is the smallest charge observed in nature and is given the name elementary charge. Each elementary charge equals 1.6×10^{-19} C. An electron has a mass of 9.1×10^{-28} g or 0.000548 **atomic mass unit (amu)**. The amu is a scale used to measure the mass of sub-atomic particles. In the amu scale, the mass of a carbon-12 atom is the standard of reference; its mass is assigned a value of 12.00000. One atomic mass unit is defined as 1/12 of the mass of the C-12 atom. This works out to be 1.66×10^{-24} g. Another convenient way to express the minuscule mass of a sub-atomic particle is in terms of energy. The energy scale uses Einstein's mass–energy relationship, $E = mc^2$, to convert all masses into units of energy. The energy unit is the **electron volt (eV)**. One electron volt is the amount of energy acquired by an electron as it accelerates across a potential difference of 1 V. An amu, when converted to energy scale, equals 931.5 MeV. The mass of an electron when converted to an energy unit is 511 keV; this is a good number to remember.

Protons and neutrons are the building blocks of nuclei. They have about the same mass of about 1 amu and are approximately 1800 times heavier than electrons. Each proton possesses a positive charge of 1.6×10^{-19} C, equal in magnitude but opposite in sign to the charge of an electron. Neutrons have no electrical charges.

There are also particles called anti-particles. Theoretical physics says that there are two universes. The universe we live in is made up of matter. The other universe is made up of **anti-matter**. Anti-particles such as positrons are sub-atomic particles of the anti-matter universe. Anti-matters are identical in every respect to matters, except for their opposite electric charge. For example, the anti-particle of the electron is the positron. The characteristics of a positron are similar in every respect to an electron, except that it carries a positive electric charge. However, anti-particles do not have a rest mass. That is, an anti-particle cannot co-exist with an ordinary particle in the matter universe. When a positron loses its kinetic energy, it crashes into a negatively charged electron. Upon collision, the positron and electron mutually annihilate each other. The mutual annihilation between an electron and a positron results in the masses of the two particles converted into two photons of 511 keV each. These two photons created from mutual annihilation of a positron and an electron are called **annihilation photons**. A mutual annihilation event results in destruction of the positron and electron masses, and the creation of two photons going away at 180° from each other.

ATOMIC MODEL

The atomic model proposed by Neils Bohr in 1913 is the simplest model to understand. In fact, all other refined atomic models, in crude approximations, reduce to the simple Bohr model. In Neils Bohr's model, an atom is composed of a positively charged nucleus containing protons and neutrons, and is surrounded by negatively charged electrons circling in well-defined **orbits** or **energy levels**. In a neutral atom, the total number of electrons in the orbits equals the number of protons in the nucleus, so there is no net electrical charge in the atom.

The Electron Cloud

In a more refined model of Bohr's atom, electrons form a cloud swarming around the nucleus instead of being confined to well-defined orbits. The electrons swarming about the nucleus may occupy any position in the vicinity of the nucleus and may even penetrate the nucleus. However, the probability of finding an electron is greatest in layers of imaginary shells surrounding the nucleus, as illustrated in Figure 1-1. One stipulation of the electron shell model is that each shell can accommodate only up to a certain maximum number of electrons.

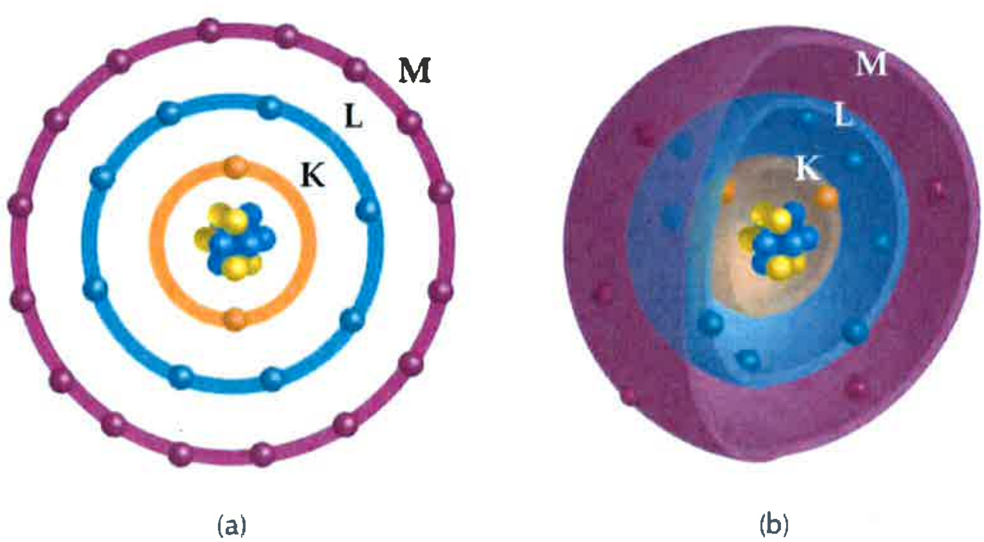

Figure 1-1. *(a)* A simple atomic model with electrons circling around the nucleus in well-defined orbits. *(b)* The shell model postulates that electrons are likely found in layers of imaginary shells surrounding the nucleus.

energy equivalent to the mass defect must be supplied to the nucleus in order to break the nucleons apart.

EXAMPLE

Calculation of the mass defect of a helium-4 atom:

$$\begin{aligned}
\text{mass of protons } 2 \times 1.007277 &= 2.014554 \text{ amu} \\
\text{mass of neutrons } 2 \times 1.008665 &= 2.017330 \\
\text{mass of electrons } 2 \times 0.000549 &= 0.001098 \\
\text{Total mass of the six individual particles} &= 4.032982 \\
\text{mass of an intact He-4 atom} &= 4.002603 \\
\text{mass defect} &= 0.030379 \text{ amu}
\end{aligned}$$

$$\text{Binding energy} = (931.5 \text{ MeV/amu}) \times (0.030379 \text{ amu}) = 29.30 \text{ MeV}.$$

When two protons, two neutrons, and two electrons are bound together to form a He-4 atom, the organized He-4 atom has a mass 0.030379 amu less than the sum of the masses of the individual particles; the sum is less than its parts. This mass defect of 0.030379 amu when translated to energy equals 29.30 MeV. In order to break up a He-4 atom, 29.30 MeV of energy must be supplied to the nucleus. The example illustrates Einstein's theory of the equivalence of mass and energy. Inside the nucleus, a certain amount of mass is converted into energy to bind the neutrons and protons together.

Nuclear Stability

Certain combinations of protons and neutrons produce stable non-radioactive nuclides, whereas others do not. The stable non-radioactive nuclides are indicated in the Chart of the Nuclides by the shaded squares as shown in Figures 1-2 and 1-3. The stable nuclides occupy a narrow band in about the middle of the chart as shown in the figures. This region is called the **stability belt**. Because most elements have several stable isotopes, the stability belt is actually a broad band rather than a narrow line as presented in many textbooks. The stability belt can be conceptualized as a broad curve, as shown in Figure 1-6, to help us assess the stability of a nuclide and its mode of radioactive decay.

At the lower end of the stability belt, the slope of the stability line is close to 45°. The neutron-to-proton ratio is nearly equal to 1 for

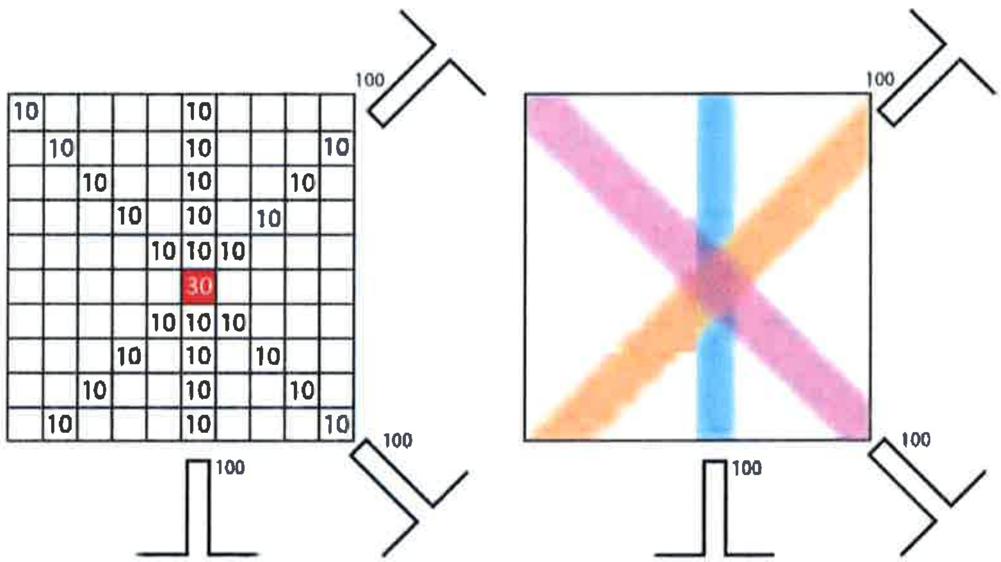

Figure 8-6. Resulting image after simple back-projection of the three profiles.

containing highly localized activities, such as the bladder activity in the patient and the point source in the example above. We can reduce the severity of streak artifacts by acquiring additional images from more projection angles, but the artifacts are still there. We are only smearing the streaks over the entire image to create a uniform background behind the point source. Images constructed from simple back-projection have poor contrast because of the high background density.

The Filtered Back-Projection Method

The filtered back-projection method reduces some of those streak artifacts by modifying the original data before back-projection. Before back-projection, each of the original projection profiles is altered by a filter function to produce a modified projection profile with a negative lobe on each side of the peak, as shown in Figure 8-7.

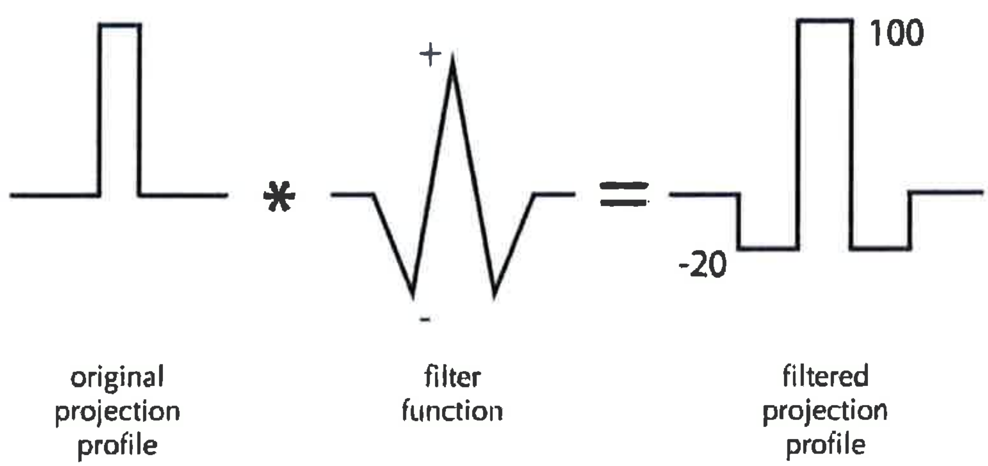

Figure 8-7. The original projection profile is modified by a filter function to produce a filtered projection profile. This process is called convolution.

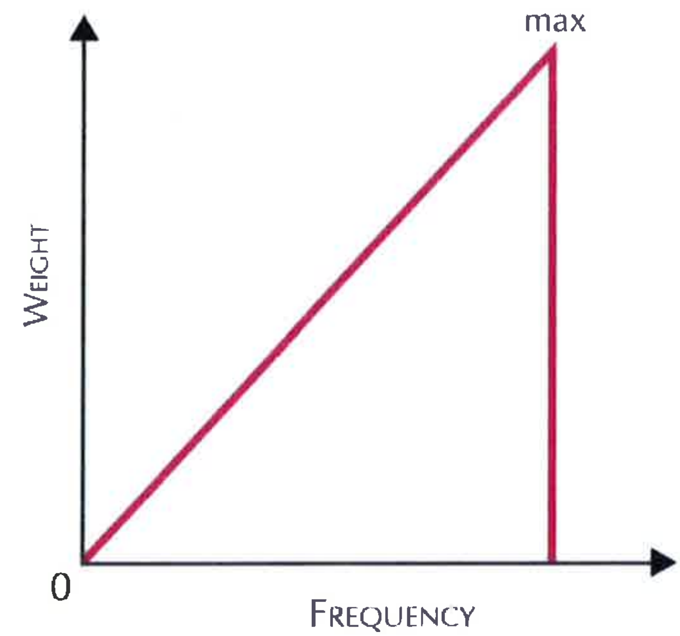

Figure 8-15. The ramp filter.

is the frequency at which the weight of the ramp filter starts to be reduced. The software that comes with the SPECT system allows the user to select the cut-off frequency in terms of the percentage of the maximum frequency that the camera/computer system can resolve. The maximum frequency that the camera/computer system can resolve is also called the **Nyquist frequency**. Cut-off frequency at 0.5 means the Butterworth window starts to reduce the slope of the ramp filter at midway from the Nyquist frequency. The order is the rapidity at which the ramp filter bends downward—higher the order, faster the ramp filter comes down to zero. The typical values used in SPECT reconstruction are the cut-off frequency 0.5 and the order 5.

The ramp filter after modified by the Butterworth window with the 0.5 cut-off frequency and order 5 is shown in Figure 8-16. The modified

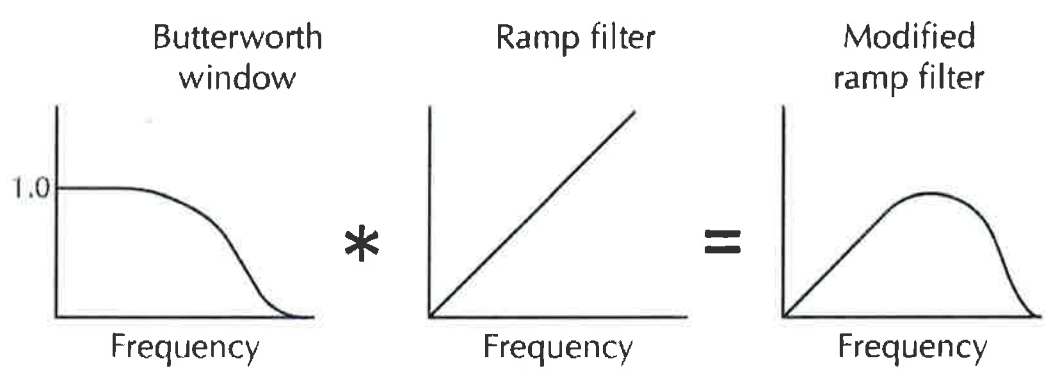

Figure 8-16. The ramp filter modified by a Butterworth window is the most commonly used filter in SPECT image reconstruction.