Physics and Radiobiology of Nuclear Medicine

Third Edition

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With 111 Figures

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Library of Congress Control Number: 2005937015

ISBN-10: 0-387-30754-0 e-ISBN 0-387-30754-0
ISBN-13: 978-0387-30754-1

Printed on acid-free paper.

Printed in the United States of America. (BS/EB)

9 8 7 6 5 4 3 2 1

springer.com

To
All my benefactors

Preface

A new edition of a book is always warranted when it needs to be updated because of advances in the field over time. Although the basics of physics, instrumentation, and radiobiology have not changed, their technological applications have been changing and improving continually. Nuclear medicine professionals worldwide appreciate the book so much that the previous edition has been published in Japanese. Changes in content and appreciation of the book are the two guiding factors in writing this third edition.

Like the previous editions, the book is aimed at residents taking the American Board of Nuclear Medicine, the American Board of Radiology (Physics part), and the American Board of Radiology with Special Competency in Nuclear Medicine examinations, and for the technologists taking the Nuclear Medicine Technology Certifying Board.

The book contains 16 chapters, and at the end of each chapter, references and suggested readings have been updated and new questions have been added where appropriate. The first 10 chapters have only minor changes because of the basic nature of the contents. A section on the chi-square test and evaluation of diagnostic tests has been added in Chapter 4. Additional radionuclides have been included in Table 5.1. In Chapter 8, the section on scintillation detectors has been rearranged and the section on dead time has been expanded. In Chapter 10, the sections on uniformity, gamma camera tuning, and quality control tests have been revised. A new section on software and DICOM has been added in Chapter 11. Chapter 12 has been revised to include SPECT/CT cameras with only minimal change in the image reconstruction by the filtered backprojection, but with a detailed description of iterative methods. Chapter 13 is a new chapter on positron emission tomography. Table 14.1 has been updated with new dose values. Chapter 15 has been expanded to include more information on cellular damage by radiation, and also a section on dirty bomb and radiation phobia. In Chapter 16, new revised NRC regulations in 10CFR35 have been added along with a new section on European regulations governing radiopharmaceuticals.

I would like to thank the members of our department for their assistance in many ways. I am thankful and grateful to Mrs. Rita Konyves for typing meticulously and conscientiously the major part of the manuscript and to Mrs. Diane Griffis for completing it.

My sincere thanks and gratitude are due to Robert Albano, Senior Clinical Medical Editor of Springer, for his constant support and encouragement, and to others at Springer for their help in the successful completion of the book.

Gopal B. Saha

Contents

1
Structure of Matter

Matter and Energy

The existence of the universe is explained by two entities: matter and energy. These two entities are interchangeable and exist in different forms to make up all things visible or invisible in the universe. Whereas matter has a definite size, shape, and form, energy has different forms but no size and shape.

Matter is characterized by its quantity, called the *mass*, and is composed of the smallest unit, the atom. In atomic physics, the unit of mass is the atomic mass unit (amu), which is equal to 1.66×10^{-27} kg.

Energy is the capacity to do work and can exist in several forms: kinetic energy (which is due to the motion of matter); potential energy (which is due to the position and configuration of matter); thermal energy (which is due to the motion of atoms or molecules in matter); electrical energy (which is due to the flow of electrons across an electric potential); chemical energy (which is due to chemical reaction); and radiation (energy in motion). Energy can change from one form to another. Of all these forms, radiation is of great importance in nuclear medicine and, therefore, will be discussed in detail.

Mass and energy are interchangeable, and one is created at the expense of the other. This is predicted by the Einstein's mass–energy relationship:

$$E = mc^2 \tag{1.1}$$

where E is energy in ergs, m is the mass in grams, and c is the velocity of light in a vacuum given as 3×10^{10} cm/sec. This relationship states that everything around us can be classified as matter or energy.

Radiation

Radiation is a form of energy in motion through space. It is emitted by one object and absorbed or scattered by another. Radiations are of two types:

1. *Particulate radiations:* Examples of these radiations are energetic electrons, protons, neutrons, α-particles, and so forth. They have mass and charge, except neutrons, which are neutral particles. The velocity of their motion depends on their kinetic energy. The particulate radiations originate from radioactive decay, cosmic rays, nuclear reactions, and so forth.

2. *Electromagnetic radiations:* These radiations are a form of energy in motion that does not have mass and charge and can propagate as either waves or discrete packets of energy, called the *photons* or *quanta*. These radiations travel with the velocity of light. Various examples of electromagnetic radiations include radio waves, visible light, heat waves, γ-radiations, and so forth, and they differ from each other in wavelength and hence in energy. Note that the sound waves are not electromagnetic radiations.

The energy E of an electromagnetic radiation is given by

$$E = h\nu = \frac{hc}{\lambda} \tag{1.2}$$

where h is the Planck constant given as 6.625×10^{-27} erg·s/cycle, ν is the frequency in hertz (Hz), defined as 1 cycle per second, λ is the wavelength in centimeters, and c is the velocity of light in vacuum, which is equal to nearly 3×10^{10} cm/s.

The energy of an electromagnetic radiation is given in electron volts (eV), which is defined as the energy acquired by an electron when accelerated through a potential difference of 1 volt. Using $1\,\text{eV} = 1.602 \times 10^{-12}$ erg, Eq. (1.2) becomes

$$E(\text{eV}) = \frac{1.24 \times 10^{-4}}{\lambda} \tag{1.3}$$

where λ is given in centimeters. Table 1.1 lists the different electromagnetic radiations along with their frequencies and wavelengths.

TABLE 1.1. Characteristics of different electromagnetic radiations.

Type	Energy (eV)	Frequency (Hz)	Wavelength (cm)
Radio, TV	10^{-10}–10^{-6}	10^{4}–10^{8}	10^{2}–10^{6}
Microwave	10^{-6}–10^{-2}	10^{8}–10^{12}	10^{-2}–10^{2}
Infrared	10^{-2}–1	10^{12}–10^{14}	10^{-4}–10^{-2}
Visible	1–2	10^{14}–10^{15}	10^{-5}–10^{-4}
Ultraviolet	2–100	10^{15}–10^{16}	10^{-6}–10^{-5}
x-Rays and γ-rays	100–10^{7}	10^{16}–10^{21}	10^{-11}–10^{-6}

TABLE 1.2. Characteristics of electrons and nucleons.

Particle	Charge	Mass (amu)*	Mass (kg)	Mass (MeV)†
Electron	–1	0.000549	0.9108×10^{-30}	0.511
Proton	+1	1.00728	1.6721×10^{-27}	938.78
Neutron	0	1.00867	1.6744×10^{-27}	939.07

* amu = 1 atomic mass unit = 1.66×10^{-27} kg = 1/12 of the mass of ^{12}C.
† 1 atomic mass unit = 931 MeV.

The Atom

For the purpose of this book, the atom can be considered as the smallest unit in the composition of matter. The atom is composed of a nucleus at the center and one or more electrons orbiting around the nucleus. The nucleus consists of protons and neutrons, collectively called *nucleons*. The protons are positively charged particles with a mass of 1.00728 amu, and the neutrons are electrically neutral particles with a mass of 1.00867 amu. The electrons are negatively charged particles with a mass of 0.000549 amu. The protons and neutrons are about 1836 times heavier than the electrons but the neutron is heavier than the proton by one electron mass (i.e., by 0.511 MeV). The number of electrons is equal to the number of protons, thus resulting in a neutral atom of an element. The characteristics of these particles are given in Table 1.2. The size of the atom is about 10^{-8} cm (called the angstrom, Å), whereas the nucleus has the size of 10^{-13} cm (termed the fermi, F). The density of the nucleus is of the order of 10^{14} g/cm^3. The electronic arrangement determines the chemical properties of an element, whereas the nuclear structure dictates the stability and radioactive transformation of the atom.

Electronic Structure of the Atom

Several theories have been put forward to describe the electronic structure of the atom, among which the theory of Niels Bohr, proposed in 1913, is the most plausible one and still holds today. The Bohr's atomic theory states that electrons rotate around the nucleus in discrete energy shells that are stationary and arranged in increasing order of energy. These shells are designated as the *K* shell, *L* shell, *M* shell, *N* shell, and so forth. When an electron jumps from the upper shell to the lower shell, the difference in energy between the two shells appears as electromagnetic radiations or photons. When an electron is raised from the lower shell to the upper shell, the energy difference is absorbed and must be supplied for the process to occur.

The detailed description of the Bohr's atomic structure is provided by the quantum theory in physics. According to this theory, each shell is designated by a quantum number *n*, called the *principal quantum number*, and

denoted by integers, for example, 1 for the K shell, 2 for the L shell, 3 for the M shell, 4 for the N shell, and 5 for the O shell. Each energy shell is subdivided into subshells or orbitals, which are designated as s, p, d, f, and so on. For a principal quantum number n, there are n orbitals in a given shell. These orbitals are assigned the *azimuthal quantum numbers*, l, which represent the electron's angular momentum and can assume numerical values of $l = 0, 1, 2 \ldots n - 1$. Thus for the s orbital, $l = 0$; the p orbital, $l = 1$; the d orbital, $l = 2$; the f orbital, $l = 3$; and so forth. According to this description, the K shell has one orbital, designated as $1s$, the L shell has two orbitals, designated as $2s$ and $2p$, and so forth. The orientation of the electron's magnetic moment in a magnetic field is described by the *magnetic quantum number*, m. The values of m can be $m = -l, -(l-1), \ldots, 0, \ldots (l-1), l$. Each electron rotates about its own axis clockwise or anticlockwise, and the *spin quantum number*, s ($s = -1/2$ or $+1/2$) is assigned to each electron to specify this rotation.

The electron configuration of the atoms of different elements is governed by the following rules:

1. No two electrons can have the same values for all four quantum numbers in a given atom.
2. The orbital of the lowest energy will be filled in first, followed by the next higher energy orbital. The relative energies of the orbitals are $1s < 2s < 2p < 3s < 3p < 4s < 3d < 4p < 5s < 4d < 5p < 6s < 4f < 5d < 6p < 7s$. This order of energy is valid for lighter elements and is somewhat different in heavier elements.
3. There can be a maximum of $2(2l + 1)$ electrons in each orbital.
4. For given values of n and l, each of the available orbitals is first singly occupied such that no electron pairing occurs. Only when all orbitals are singly occupied does electron pairing take place.
5. Each energy shell contains a maximum of $2n^2$ electrons.

The hydrogen atom has one proton in the nucleus and one electron in the orbit. Its electronic structure is represented as $1s^1$. The helium atom has two electrons, which are accommodated in the 1s orbital, and thus has the structure of $1s^2$. Now let us consider the structure of $^{16}_{8}O$, which has eight electrons. The first two electrons will fill the $1s$ orbital. The next two electrons will go to the $2s$ orbital. There are three p orbitals, designated as p_x, p_y, p_z, which will be occupied by three electrons individually. The eighth electron will occupy the p_x orbital pairing with the electron already in it. Thus, the electronic configuration of $^{16}_{8}O$ is given by $1s^2 2s^2 2p^4$.

The electron configurations in different orbitals and shells are illustrated in Table 1.3, and the structure of $_{28}Ni$ is shown in Figure 1.1.

The electronic structure of the atom characterizes the chemical properties of elements. The outermost shell in the most stable and chemically inert elements such as neon, argon, krypton, and xenon has the electronic structure of ns^2np^6. Helium, although a noble gas, has the $1s^2$ configuration.

TABLE 1.3. Electron configurations in different energy shells.

Principal shell	Principal quantum number (n)	Orbital (l)	No. of electrons = $2(2l + 1)$ in each orbital	$2n^2$
K	1	$s(0)$	2	2
L	2	$s(0)$	2	
		$p(1)$	6	8
M	3	$s(0)$	2	
		$p(1)$	6	
		$d(2)$	10	18
N	4	$s(0)$	2	
		$p(1)$	6	
		$d(2)$	10	
		$f(3)$	14	32
O	5	$s(0)$	2	
		$p(1)$	6	
		$d(2)$	10	
		$f(3)$	14	
		$g(4)$	18	50

Elements having electronic configurations different from that of the noble gases either lose or gain electrons to achieve the structure ns^2np^6 of the nearest noble gas atom. The electrons in these shells are called the *valence electrons* and are primarily responsible for the chemical bond formation.

Electrons in different shells are held by *binding energy* in different shells of the atom. The binding energy of an electron is defined as the energy that is required to be supplied to remove it completely from a shell. The binding energy of the electron is the greatest in the K shell and decreases with higher shells such as L, M, and so on. The binding energy also increases with increasing atomic number of the elements. Thus, the K-shell binding energy (21.05 keV) of technetium, with atomic number 43, is higher than the K-shell binding energy (1.08 keV) of sodium, with atomic number 11. The K-shell binding energy of electrons in several elements are: carbon, 0.28 keV, gallium, 10.37 keV, technetium, 21.05 keV; indium, 27.93 keV; iodine, 33.16 keV; lead, 88.00 keV.

When an electron is removed completely from an atom, the process is called *ionization*. The atom is said to be ionized and becomes an ion. On

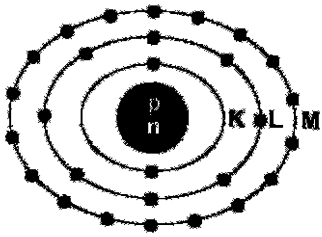

FIG. 1.1. The electronic configuration of $_{28}$Ni. The K shell has 2 electrons, the L shell has 8 electrons, and the M shell has 18 electrons.

the other hand, when the electron is raised from a lower energy shell to an upper energy shell, the process is called *excitation*. Both ionization and excitation processes require a supply of energy from outside the atom such as heating, applying an electric field, and so forth. In the excited atoms, electrons jump from the upper energy shell to the lower energy shell to achieve stability. The difference in energy appears as electromagnetic radiations or photons. Thus, if the binding energy of *K*-shell electrons in, say, bromine is 13.5 keV and the *L*-shell binding energy is 1.8 keV, the transition of electrons from the *L* shell to the *K* shell will occur with the emission of 11.7 keV (13.5 – 1.8 = 11.7 keV) photons. As we shall see later, these radiations are called the *characteristic x-rays* of the product atom.

Structure of the Nucleus

As already stated, the nucleus of an atom is composed of protons and neutrons. The number of protons is called the *atomic number* of the element and denoted by *Z*. The number of neutrons is denoted by *N*, and the sum of the protons and neutrons, $Z + N$, is called the *mass number*, denoted by *A*. The symbolic representation of an element, *X*, is given by ${}^{A}_{Z}X_{N}$. For example, sodium has 11 protons and 12 neutrons with a total of 23 nucleons. Thus, it is represented as ${}^{23}_{11}Na_{12}$. However, the atomic number *Z* of an element is known, and *N* can be calculated as $A - Z$; therefore, it suffices to simply write ^{23}Na (or Na-23).

To explain the various physical observations related to the nucleus of an atom, two models for the nuclear structure have been proposed: the liquid drop model and the shell model. The liquid drop model was introduced by Niels Bohr and assumes a spherical nucleus composed of closely packed nucleons. This model explains various phenomena, such as nuclear density, energetics of particle emission in nuclear reactions, and fission of heavy nuclei.

In the shell model, both protons and neutrons are arranged in discrete energy shells in a manner similar to the electron shells of the atom in the Bohr atomic theory. Similar to the electronic configuration of the noble gas atoms, nuclei with 2, 8, 20, 28, 50, 82, or 126 protons or neutrons are found to be very stable. These nucleon numbers are called the *magic numbers*.

It is observed that atomic nuclei containing an odd number of protons or neutrons are normally less stable than those with an even number of protons or neutrons. Thus, nuclei with even numbers of protons and neutrons are more stable, whereas those with odd numbers of protons and neutrons are less stable. For example, ^{12}C with six protons and six neutrons is more stable than ^{13}C containing six protons and seven neutrons.

There are about 270 stable atoms of naturally occurring elements. The stability of these elements is dictated by the configuration of protons and neutrons. The ratio of the number of neutrons to the number of protons (N/Z) is an approximate indicator of the stability of a nucleus. The N/Z ratio

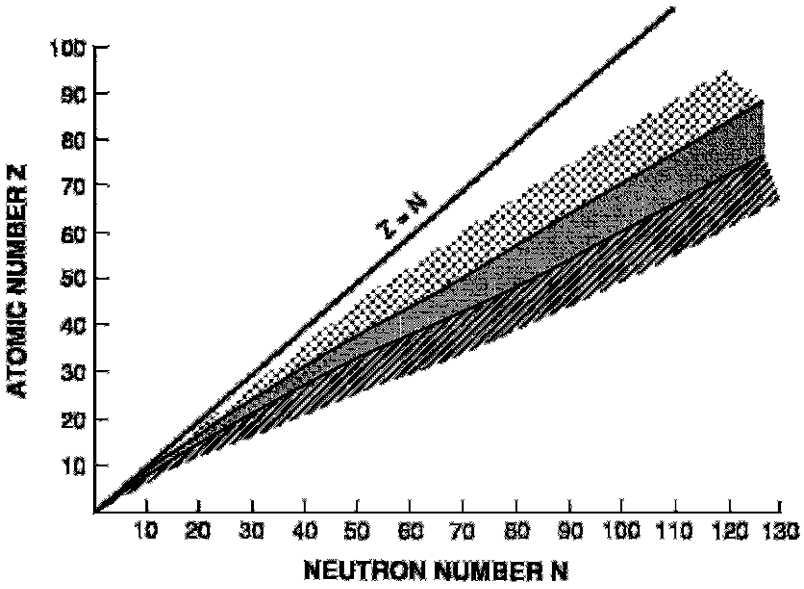

FIG. 1.2. The plot of atomic number (Z) versus the number of neutrons (N) for all nuclides. The proton-rich nuclides fall on the left (dotted) and the neutron-rich nuclides fall on the right (cross-hatched) of the line of stability, indicated by the dark-shaded area. The solid line represents nuclides with $Z = N$.

is 1 in low-Z elements such as $^{12}_{6}$C, $^{14}_{7}$N, and $^{16}_{8}$O, but it increases with increasing atomic number of elements. For example, it is 1.40 for $^{127}_{53}$I and 1.54 for $^{208}_{82}$Pb. The plot of the atomic number versus the neutron number of all nuclides is shown in Figure 1.2. All stable nuclear species fall on or around what is called the *line of stability*. The nuclear species on the left side of the line have fewer neutrons and more protons; that is, they are proton-rich. On the other hand, those on the right side of the line have fewer protons and more neutrons; that is, they are neutron-rich. The nuclides away from the line of stability are unstable and disintegrate to achieve stability.

Nuclear Binding Energy

According to the classical electrostatic theory, the nucleus of an atom cannot exist as a single entity, because of the electrostatic repulsive force among the protons in the nucleus. The stability of the nucleus is explained by the existence of a strong binding force called the *nuclear force*, which overcomes the repulsive force of the protons. The nuclear force is effective equally among all nucleons and exists only in the nucleus, having no influence outside the nucleus. The short range of the nuclear force leads to a very small size ($\sim 10^{-13}$ cm) and very high density ($\sim 10^{14}$ g/cm^3) of the nucleus.

The mass M of a nucleus is always less than the combined masses of the nucleons A in the nucleus. The difference in mass $(M - A)$ is termed the *mass defect*, which has been used as binding energy for all nucleons in the nucleus. The average binding energy of a nucleon is equal to the total binding energy (calculated from the mass defect) divided by the number of nucleons. It is of the order of 6–9 MeV, although the binding energy of an individual nucleon has a definite value, depending on the shell it occupies. The binding energy of a nucleon must be supplied to completely remove it from the nucleus. Note that whereas the binding energy of the nucleons is in the megaelectron volt (MeV) range, the electron binding energy in the atomic orbital is of the order of kiloelectron volts (keV), a factor of 1000 lower.

Nuclear Nomenclature

A *nuclide* is an atomic species with a definite number of protons and neutrons arranged in a definite order in the nucleus.

Radionuclides are those nuclides that are unstable and thus decay by emission of particles or electromagnetic radiations or by spontaneous fission.

Isotopes are the nuclides having the same atomic number Z but different mass number A. Isotopes exhibit the same chemical properties. Examples of carbon isotopes are $^{11}_{6}C$, $^{12}_{6}C$, and $^{13}_{6}C$.

Isotones are the nuclides having the same number of neutrons N but different numbers of protons. Examples of isotones are: $^{134}_{55}Cs$, $^{133}_{54}Xe$, and $^{132}_{53}I$, each having 79 neutrons.

Isobars are the nuclides with the same number of nucleons, that is, the same mass number A, but a different combination of protons and neutrons. For example: ^{82}Y, ^{82}Sr, ^{82}Rb, and ^{82}Kr are all isobars having the mass number 82.

Isomers are the nuclides with the same number of protons and neutrons, but having different energy states and spins. ^{99}Tc and ^{99m}Tc are isomers of the same nuclide. Individual nuclides can exist in different energy states above the ground state due to excitation. These excited states are called the *isomeric states*, which can have a lifetime varying from picoseconds to years. When the isomeric states are long-lived, they are referred to as *metastable states*. These states are denoted by "m" as in ^{99m}Tc.

Chart of the Nuclides

Nearly 3000 nuclides, both stable and unstable, are arranged in the form of a chart, called the *chart of the nuclides*, a section of which is presented in Figure 1.3. Each square in the chart represents a specific nuclide,

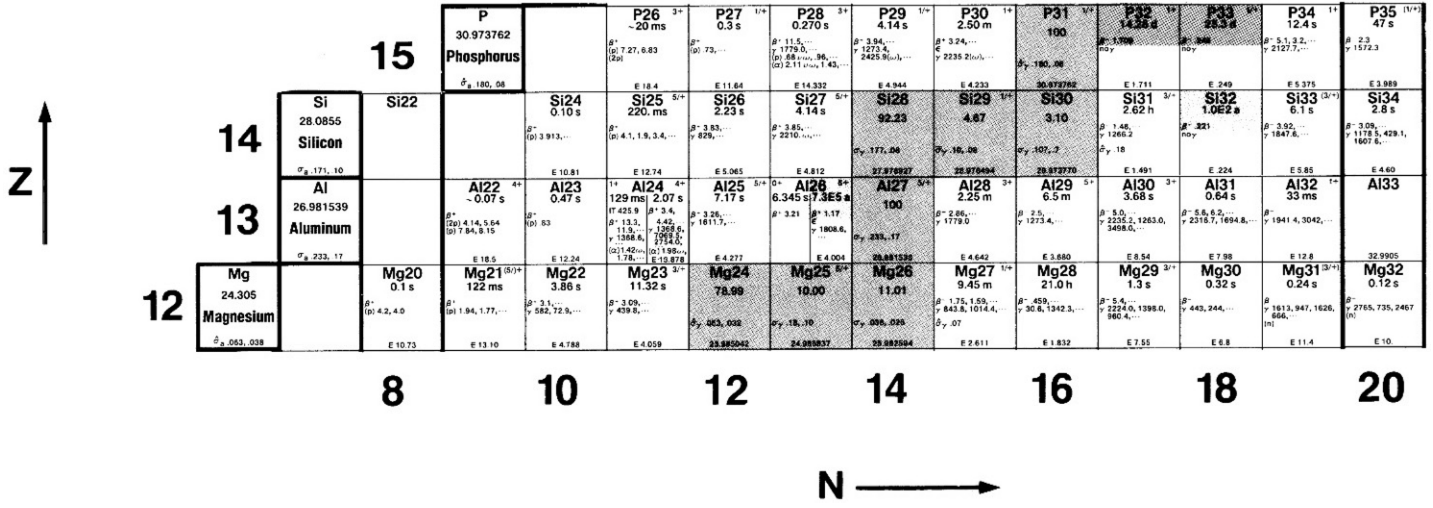

FIG. 1.3. A section of the chart of nuclides. (Courtesy of Knolls Atomic Power Laboratory, Schenectady, New York, operated by the General Electric Company for Naval Reactors, the U.S. Department of Energy.)

containing various information such as the half-life, type and energy of radiations, and so forth of the nuclide, and neutron capture cross section of the stable nuclide. The nuclides are arranged in increasing neutron number N horizontally and in increasing proton number Z vertically. Each horizontal group of squares contains all isotopes of the same element, whereas the vertical group contains all isotones with the same number of neutrons. For isomers, the square is subdivided into sections representing each isomer.

Questions

1. If a mass of matter (m) is converted to electromagnetic radiation, what should be the energy of this radiation?
2. Describe the Bohr's atomic theory in terms of the electronic configuration of the atom.
3. What is the difference between the orbital electron binding energy and the nuclear binding energy of an atom?
4. Define the mass defect and mass number of an atom. What does the mass defect account for?
5. Write the electronic configuration of ^{99m}Tc and ^{131}I.
6. How many electrons can the 3d orbital contain?
7. The electron binding energy of the K shell in an atom is higher than that of the L shell. True or false?
8. What is the difference between ionization and excitation of an atom?
9. What is a metastable state of a nuclide? How is it designated?

Suggested Readings

Evans RD. *The Atomic Nucleus.* Malabar, FL: Kreiger; 1982.

Friedlander G, Kennedy TW, Miller JM. *Nuclear and Radiochemistry*. 3rd ed. New York: Wiley; 1981.

Turner JE. *Atoms, Radiation, and Radiation Protection.* 2nd ed. New York: Wiley; 1995.

2
Radioactive Decay

In 1896, Henri Becquerel first discovered natural radioactivity in potassium uranyl sulfate. Artificial radioactivity was not produced until 1934, when I. Curie and F. Joliot made boron, aluminum, and magnesium radioactive by bombarding them with α-particles from polonium. This introduction of artificial radioactivity prompted the invention of cyclotrons and reactors in which many radionuclides are now produced. So far, more than 2700 radionuclides have been artificially produced and characterized in terms of their physical properties.

Radionuclides are unstable and decay by emission of particle or γ-radiation to achieve stable configuration of protons and neutrons in the nucleus. As already mentioned, the stability of a nuclide in most cases is determined by the N/Z ratio of the nucleus. Thus, as will be seen later, whether a nuclide will decay by a particular particle emission or γ-ray emission is determined by the N/Z and/or excitation energy of the nucleus. Radionuclides can decay by one or more of the six modes: *spontaneous fission, isomeric transition (IT), alpha (α) decay, beta (β^-) decay, positron (β^+) decay, and electron capture (EC) decay.* In all decay modes, energy, charge, and mass are conserved. Different decay modes of radionuclides are described later in detail.

Spontaneous Fission

Fission is a process in which a heavy nucleus breaks into two fragments accompanied by the emission of two or three neutrons. The neutrons carry a mean energy of 1.5 MeV and the process releases about 200 MeV energy that appears mostly as heat.

Spontaneous fission occurs in heavy nuclei, but its probability is low and increases with mass number of the nuclei. The half-life for spontaneous fission is 2×10^{17} years for ^{235}U and only 55 days for ^{254}Cf. As an alternative to the spontaneous fission, the heavy nuclei can decay by α-particle or γ-ray emission.

Isomeric Transition

As previously mentioned, a nucleus can exist in different energy or excited states above the ground state, which is considered as the state involving the arrangement of protons and neutrons with the least amount of energy. These excited states are called the *isomeric states* and have lifetimes of fractions of picoseconds to many years. When isomeric states are long-lived, they are referred to as *metastable states* and denoted by "m" as in ^{99m}Tc. An excited nucleus decays to a lower energy state by giving off its energy, and such transitions are called isomeric transitions (ITs). Several isomeric transitions may occur from intermediate excited states prior to reaching the ground state. As will be seen later, a parent radionuclide may decay to an upper isomeric state of the product nucleus by α-particle or β-particle emission, in which case the isomeric state returns to the ground state by one or more isomeric transitions. A typical isomeric transition of ^{99m}Tc is illustrated in Figure 2.1. Isomeric transitions can occur in two ways: gamma (γ)-ray emission and internal conversion.

Gamma (γ)-Ray Emission

The common mode of an isomeric transition from an upper energy state of a nucleus to a lower energy state is by emission of an electromagnetic radiation, called the γ-ray. The energy of the γ-ray emitted is the difference between the two isomeric states. For example, a decay of a 525-keV isomeric state to a 210-keV isomeric state will result in the emission of a 315-keV γ-ray.

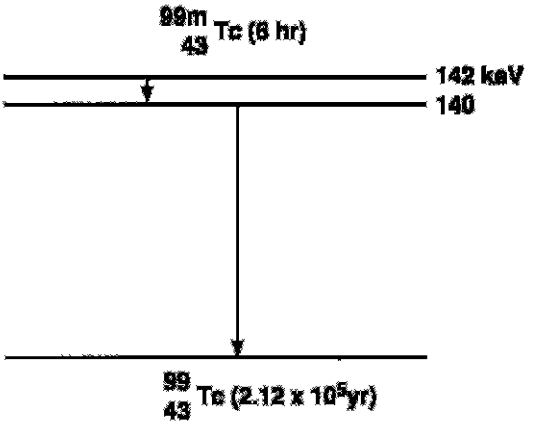

FIG. 2.1. Isomeric transition of ^{99m}Tc. Ten percent of the decay follows internal conversion.

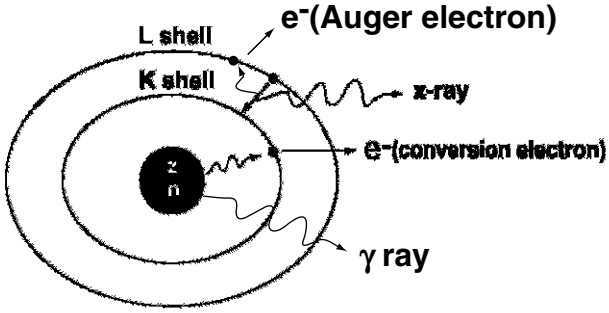

FIG. 2.2. Internal conversion process. The excitation energy of the nucleus is transferred to a *K*-shell electron, which is then ejected, and the *K*-shell vacancy is filled by an electron from the *L* shell. The energy difference between the *L* shell and *K* shell appears as the characteristic *K* x-ray. Alternatively, the characteristic K x-ray may transfer its energy to an L-shell electron, called the Auger electron, which is then ejedted.

Internal Conversion

An alternative to the γ-ray emission is the *internal conversion* process. The excited nucleus transfers the excitation energy to an orbital electron—preferably the *K*-shell electron—of its own atom, which is then ejected from the shell, provided the excitation energy is greater than the binding energy of the electron (Fig. 2.2). The ejected electron is called the *conversion electron* and carries the kinetic energy equal to $E_\gamma - E_B$, where E_γ is the excitation energy and E_B is the binding energy of the electron. Even though the *K*-shell electrons are more likely to be ejected because of the proximity to the nucleus, the electrons from the *L* shell, *M* shell, and so forth also may undergo the internal conversion process. The ratio of the number of conversion electrons (N_e) to the number of observed γ-radiations (N_γ) is referred to as the *conversion coefficient*, given as $\alpha = N_e/N_\gamma$. The conversion coefficients are subscripted as α_K, α_L, α_M . . . depending on which shell the electron is ejected from. The total conversion coefficient α_T is then given by

$$\alpha_T = \alpha_K + \alpha_L + \alpha_M + \cdots$$

Problem 2.1
If the total conversion coefficient (α_T) is 0.11 for the 140-keV γ-rays of ^{99m}Tc, calculate the percentage of 140-keV γ-radiations available for imaging.

Answer

$$\alpha_T = \frac{N_e}{N_\gamma} = 0.11$$

$$N_e = 0.11\, N_\gamma$$

Total number of disintegrations

$$= N_e + N_\gamma$$
$$= 0.11N_\gamma + N_\gamma$$
$$= 1.11N_\gamma$$

Thus, the percentage of γ-radiations

$$= \frac{N_\gamma}{1.11N_\gamma} \times 100$$
$$= \frac{1}{1.11} \times 100$$
$$= 90\%$$

An internal conversion process leaves an atom with a vacancy in one of its shells, which is filled by an electron from the next higher shell. Such situations may also occur in nuclides decaying by electron capture (see later). When an L electron fills in a K-shell vacancy, the energy difference between the K shell and the L shell appears as a *characteristic K x-ray*. Alternatively, this transition energy may be transferred to an orbital electron, which is emitted with a kinetic energy equal to the characteristic x-ray energy minus its binding energy. These electrons are called *Auger electrons*, and the process is termed the *Auger process*, analogous to internal conversion. The Auger electrons are monoenergetic. Because the characteristic x-ray energy (energy difference between the two shells) is always less than the binding energy of the K-shell electron, the latter cannot undergo the Auger process and cannot be emitted as an Auger electron.

The vacancy in the shell resulting from an Auger process is filled by the transition of an electron from the next upper shell, followed by emission of similar characteristic x-rays and/or Auger electrons. The fraction of vacancies in a given shell that are filled by emitting characteristic x-ray emissions is called the *fluorescence yield*, and the fraction that is filled by the Auger processes is the *Auger yield*. The Auger process increases with the increasing atomic number of the atom.

Alpha (α)-Decay

The α-decay occurs mostly in heavy nuclides such as uranium, radon, plutonium, and so forth. Beryllium-8 is the only lightest nuclide that decays by breaking up into two α-particles. The α-particles are basically helium ions with two protons and two neutrons in the nucleus and two electrons removed from the helium atom. After α-decay, the atomic number of the nucleus is reduced by 2 and the mass number by 4.

$$^{222}_{86}\text{Rn} \rightarrow {}^{218}_{84}\text{Po} + \alpha$$

The α-particles from a given radionuclide all have discrete energies corresponding to the decay of the initial nuclide to a particular energy level of the product (including, of course, its ground state). The energy of the α-particles is, as a rule, equal to the energy difference between the two levels and ranges from 1 to 10 MeV. The high-energy α-particles normally originate from the short-lived radionuclides and vice versa. The range of the α-particles is very short in matter and is approximately 0.03 mm in body tissue. The α-particles can be stopped by a piece of paper, a few centimeters of air, and gloves.

Beta (β^-)-Decay

When a radionuclide is neutron rich—that is, the N/Z ratio is greater than that of the nearest stable nuclide—it decays by the emission of a β^--particle (note that it is an electron*) and an antineutrino, $\overline{\nu}$. In the β^--decay process, a neutron is converted to a proton, thus raising the atomic number Z of the product by 1. Thus:

$$n \rightarrow p + \beta^- + \overline{\nu}$$

The difference in energy between the parent and daughter nuclides is called the *transition or decay energy*, denoted by E_{max}. The β^--particles carry E_{max} or part of it, exhibiting a spectrum of energy as shown in Figure 2.3. The average energy of the β^--particles is about one-third of E_{max}. This observation indicates that β^--particles often carry only a part of the transition energy, and energy is not apparently conserved in β^--decay. To satisfy the law of energy conservation, a particle called the *antineutrino*, $\overline{\nu}$, with no charge and a negligible mass has been postulated, which carries the remainder of E_{max} in each β^--decay. The existence of antineutrinos has been proven experimentally.

After β^--decay, the daughter nuclide may exist in an excited state, in which case, one or more γ-ray emissions or internal conversion will occur to dispose of the excitation energy. In other words, β^--decay is followed by isomeric transition if energetically permitted.

The decay process of a radionuclide is normally represented by what is called the *decay scheme*. Typical decay schemes of ^{131}I and ^{99}Mo are shown in Figures 2.4 and 2.5, respectively. The β^--decay is shown by a left-to-right arrow from the parent nuclide to the daughter nuclide, whereas the isomeric transition is displayed by a vertical arrow between the two states.

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* The difference between a β^--particle and an electron is that a β^--particle originates from the nucleus, and an electron originates from the extranuclear electron orbitals.

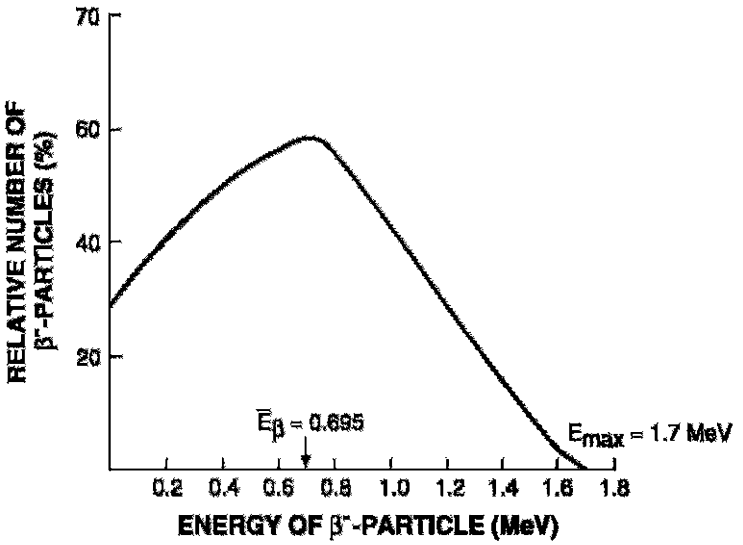

FIG. 2.3. A typical energy spectrum of the β^--particles of ^{32}P.

(Note: The β^+-decay is shown by a two-step right-to-left arrow between the two states, the electron capture decay by a right-to-left arrow, and the α-decay by a down arrow). Although it is often said that ^{131}I emits 364-keV γ-rays, it should be understood that the 364-keV γ-ray belongs to ^{131}Xe as

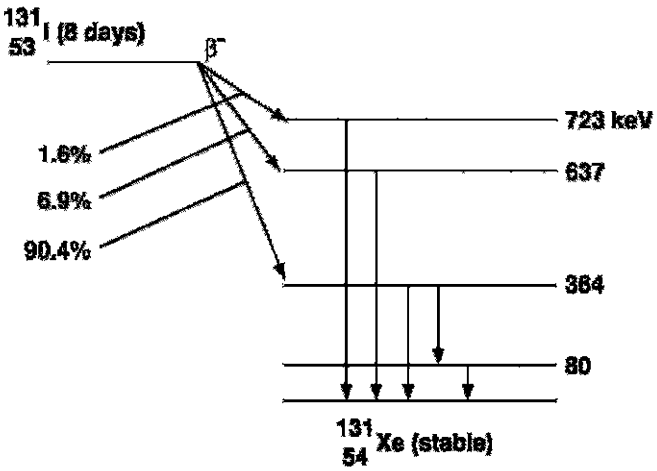

FIG. 2.4. Decay scheme of ^{131}I. Eighty-one percent of the total ^{131}I radionuclides decay by 364-keV γ-ray emission. The 8.0-day half-life of ^{131}I is shown in parentheses.