CORRELATIVE IMAGING

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MAGNETIC RESONANCE
COMPUTED TOMOGRAPHY
ULTRASOUND

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FOREWORD

The philosopher Pierre Teilhard de Chardin wrote that the history of the living world can be summarized as the elaboration of ever more perfect eyes, within a cosmos in which there is always something more to be seen.

When a person feels sick, his or her family, friends, and physicians try to understand what is wrong with him or her and what can be done about it. The process usually involves putting the label of a disease upon the illness (making the diagnosis) so the problem can be approached scientifically, enabling prognosis and treatment. Fundamental to the diagnostic process is the question of the nature of disease, which can be defined as a deviation from what is normal. In the standard nomenclature of diseases, the classification is based on anatomy and cause, the latter including microorganisms, toxins, and other environmental factors. In many cases, diseases are identified by symptoms and signs that represent patterned responses of the body to the noxious environmental forces, such as fever or pain, rather than the disease process itself.

Hippocrates, the father of physiological medicine, and his colleagues saw diseases as processes in time. This formed the essence of physiology and biochemistry. The nature of disease was grounded in the nature of man, and a predominance of one or more of the four humors (blood, phlegm, black bile, and yellow bile) determined the person's temperament. Disease was the result of imbalance.

The approach to treatment depends on the concept of disease. The use of anatomy and morbid pathology in defining diseases began when Vesalius extended the work of Galen by relating case histories of patients to the anatomical findings at autopsy. The anatomical approach was suited perfectly to surgical treatment, and the discovery of x-rays by Roentgen was a landmark in the advance of the anatomical approach to illness, which even today dominates much of medicine.

The end of World War II marked the introduction into medicine of carbon-14 and tritium, which provided the foundation of modern biochemistry and much of clinical medicine.

Advances in the use of radioactive tracers, particularly cyclotron-produced carbon-11 and fluorine-18 have made it possible to extend biochemistry from the study of body fluids to the study of the chemistry of body organs and parts of organs in living human beings. We have gone from the study of black bile to the study of dopamine.

The anatomical detail provided by magnetic resonance imaging, the newest of the new "eyes" with which to view the body in health and disease, has provided information equal to and often surpassing the anatomical information obtainable at the operating table or even at autopsy. The newest eyes are positron-emission and single-photon-emission computed tomography to reveal chemistry and physiology, and magnetic resonance imaging to reveal anatomy. Increasing concern over the carcinogenic effects of ionizing radiation is likely to be another factor in the advance of magnetic resonance imaging in modern medicine.

The modern physician faces an increasingly broad choice of eyes to help him or her solve a particular patient's problem. While it is true that the greatest costs of medicine do not lie in diagnostic procedures (which today comprise about 6-7% of the total costs of hospitalization), nevertheless, the most effective care of the patient depends on the accuracy and completeness of the knowledge about the patient and his or her illness. Ignorance remains the greatest cause of high costs, but it behooves the physicians responsible for trying to understand what is wrong with the patient, what is going to happen to him or her, and what can be done about it, to integrate the diagnostic modalities into a coherent whole.

While specialization is inevitable, it is essential to have persons who can digest the vast amount of information available about the patient. There must be a harmony of observation and thought. A patient can be viewed from so many angles that disconnected pictures are obtained. Images accumulate, but the patient sometimes dies.

This book is a step in the direction of integration of medical imaging. While it is impossible for a single person to become expert in all aspects of medical imaging, including nuclear medicine, magnetic resonance, computed tomography, and ultrasound, the book provides a basic text for those entering a field of medical imaging, and provides an excellent, broad overview that can then be extended by more specialized texts and personal experience.

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FOREWORD

The role of nuclear medicine in the modern medical diagnostic workup has been challenged recently by the increasing use of magnetic resonance imaging (MRI) and earlier tomographic imaging modalities i.e., computed tomography (CT) and ultrasound. This text addresses that challenge. The Vanderbilt authors are radiologists skilled (and well published) not only in nuclear medicine and MRI but also in CT, ultrasound, and other imaging modalities with which the nuclear medicine images are correlated.

The focus of this book is practical: how does one best use nuclear medicine when MRI, CT, and ultrasound are also available? How do the relative strengths, deficits, and costs of nuclear medicine compare with MRI, CT, and ultrasound in the evaluation of a particular symptom complex? These questions lead naturally to a discussion of the gatekeeper functions of the radiologist in an environment prone to increasing fiscal austerity.

The practical focus of this book is reflected in the chapter titles: "Physics," "Quality Control," "Clinical Correlation," etc. In a sense, this is a "how-to" book reflecting the extensive experience of the Vanderbilt group with these various imaging modalities. While the clinical discussion centers on the applications of nuclear medicine, there is significant discussion and correlation with MRI and, where appropriate, with CT, ultrasound, and the more traditional radiographic techniques. In addition to its practical aspects, the text provides a solid review not only of physics but also of the clinical aspects of disease. Clinical discussion starts from a detailed explanation of the pathophysiology of the particular disease process, reflecting the first author's strong background in internal medicine.

As radiology continues to expand with the implementation of newer modalities such as MRI, there is an increasing need to reexamine the indications for nuclear medicine. This text does that in an unbiased manner using practical clinical examples. Current medical practice (and reimbursement) no longer permits all tests to be ordered on all patients. As discussed in the final chapter, modern radiologists must be aware of the relative attributes as well as the costs of the various diagnostic procedures at their disposal in order for the workup to proceed in the most cost effective manner. Given the current cries for containment of medical costs, we physicians had better assume these gatekeeper functions or they will fall to non-M.D. bureaucrats.

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PREFACE

Nuclear medicine, magnetic resonance imaging, computed tomography, and ultrasound are extremely important diagnostic tools for clinical diagnosis and have transformed radiology into a multimodality imaging specialty. The technological complexities associated with these modalities have caused a significant increase in the requirement for comprehensive understanding of their relative capabilities in providing diagnostic information on specific disease states. We therefore believe that a need exists for a single text covering the correlative approach to diagnostic medical imaging. It is our intent to present this complex material in sufficient depth so that it will be of value to both the specialist physician and the resident trainee. *Correlative Imaging* is designed to be used in the private practice milieu as well as in training programs for physicians who desire to become specialists in the various fields of diagnostic imaging.

Section 1 of the text (Chapters 1 to 9) is devoted to physical principles, instrumentation, and quality assurance of the different imaging modalities. Also included in this section is an in-depth review of radiopharmaceuticals and contrast agents used in both radiographic diagnosis and magnetic resonance imaging. The physical principles associated with medical imaging are complex, and we have consistently attempted to present this material with clarity and with reference to clinical applications whenever possible.

Section 2 of the text (Chapters 10 to 27) includes detailed discussions of clinical multimodality imaging in adult and pediatric patients. This section is subdivided into organ systems with special reference to peripheral vascular imaging (Chapter 12) and inflammatory imaging (Chapter 26). Advantages, limitations, and clinical relationships are discussed in detail. Chapter 27 provides a review of the continually changing environment related to economic and marketing considerations in medical imaging.

The appendix provides an update on radiation protection in nuclear medicine with specific emphasis on values, regulations, and source materials.

The introduction of diagnostically related groups (DRGs) and the problem of rising medical costs make the importance of reaching a diagnosis by the most direct and cost-effective method paramount. The responsibility to the patient and the medical care system rests with the physician. This book has been written to provide the imaging physician with a broad background of information regarding the potential limitations and relative values of the various imaging modalities currently available.

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James A. Patton
Thomas A. Powers
Max I. Shaff
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ACKNOWLEDGMENTS

There are numerous people who were essential in the construction and publication of this book. We would like to acknowledge Virginia Brocker and Tina Romine for their editorial assistance and John Bobbit for his photography. We would especially like to thank Timothy Grayson, Editor, Carol Eckhart, Associate Editor, and Theda Harris and Ann Seitz, Production Sponsors at Williams & Wilkins for their outstanding contributions and assistance throughout this project. A special thanks to Sharon Phillips for her secretarial help in the early difficult stages of this book. Our gratitude is also extended to the authors and publishers who generously granted permission to reproduce illustrations from other books and journals.

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CONTENTS

SECTION

1

Principles and Instrumentation

1

Nuclear Medicine, Physics, and Instrumentation

James A. Patton

Nuclear medicine imaging techniques are performed by administering pharmaceuticals that are labeled or tagged with radioisotopes so that they are preferentially accumulated in the organs of interest. Images are then obtained using detection systems that are sensitive to the kinds of radiation emitted from the administered radiotracers. These images do not possess the spatial resolution of other imaging modalities; however, the information provided to the clinicians is generally of a different type, namely functional information. It is only through an understanding of the basic underlying physical principles associated with radioactive decay and interactions of radiation with matter that an adequate level of comprehension of nuclear medicine imaging procedures can be achieved.

Atomic Physics

The smallest subdivision of matter that retains the original physical and chemical properties of the matter is referred to as a molecule. Molecules can be broken down further into basic fundamental building blocks, or atoms, of which all matter is composed. Molecules of an element contain a single type of atom. Molecules of compounds are composed of different types of atoms.

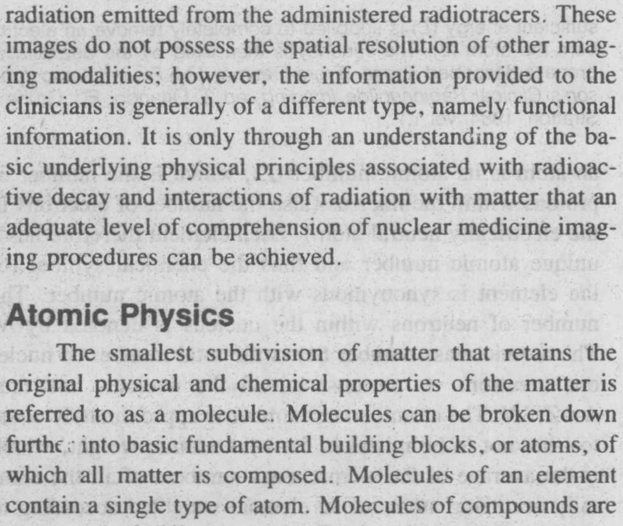

Figure 1.1. Modern simplified concept of the atom (Bohr model). (From Freeman LM: *Freeman and Johnson's Clinical Radionuclide Imaging*, ed 3. Orlando, FL, Grune & Stratton, 1984, vol 1.)

The current simplified concept of the atom is shown in Figure 1.1. It is composed of a positively charged nucleus containing positively charged protons and electrically neutral neutrons. Surrounding the nucleus in discrete orbits or shells are enough negatively charged electrons to make the atom electrically neutral (i.e., the proton number equals the electron number). These particles are summarized in Table 1.1. The shells are denoted by letters of the alphabet, with the innermost shell being the *K* shell. The next shell is identified by the letter *L*, the next *M*, and so forth. The shells are also identified by an integer number referred to as the principal quantum number, *n*. For the *K* shell $n = 1$, for the *L* shell $n = 2$, for the *M* shell $n = 3$, and so forth. Each shell can contain a maximum of $2n^2$ electrons, and is actually composed of $2n - 1$ subshells, each with slightly different characteristics.

The electrons are held in their orbits by the coulomb attractive force between them and the positively charged nucleus. In the ground state, the atom is in its most stable configuration with the electrons positioned as closely as possible to the nucleus in the allowed inner orbits. It is in these positions that the force of attraction is greatest, and it is here that the electrons are most tightly bound. The energy required to completely remove an electron from a particular shell within an atom is termed the binding energy of that shell. Binding energies for a particular shell increase with increasing positive charge of the nucleus. For a given atom, binding energies decrease in moving from inner to outer shells. Thus, in order to move an electron from an inner shell to an outer shell, energy must be supplied to the electron. This process is called excitation, and the energy supplied must be at least equal to the difference in binding energies of the two shells. Conversely, when an electron moves from an outer shell to an inner shell, this same amount of energy must be released in the process. This process is called deexcitation and results in the emission of either a characteristic x-ray or an Auger (pronounced oh-zhay) electron (Fig. 1.2A). The characteristic x-rays are

Table 1.1. Subatomic Particles

Name	Symbol	Charge	Mass (gm)	Relative Mass
Electron	e^-	−1	0.9108×10^{-27}	1
Proton	p	+1	1.6724×10^{-24}	1836
Neutron	n	0	1.6747×10^{-24}	1840

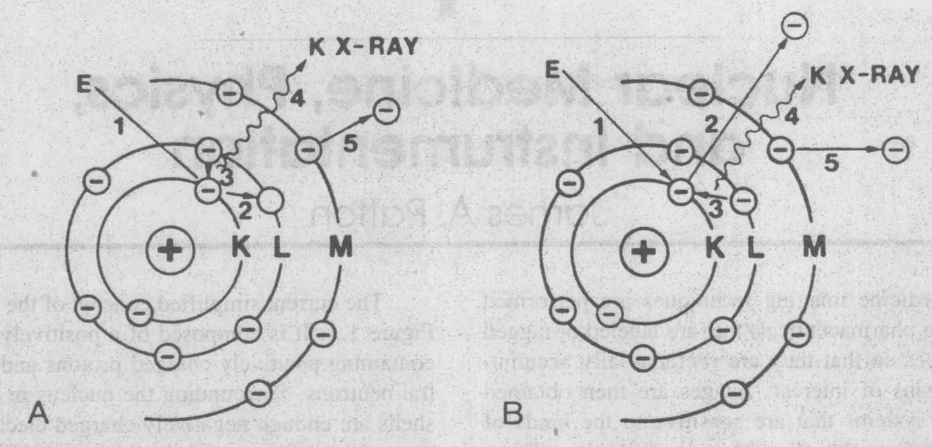

Figure 1.2. **A**, In the excitation process, energy (*E*) is supplied to an orbital electron (*1*), moving it to an outer shell (*2*). The atom is deexcited when an outer-shell electron drops down to fill the vacancy (*3*). The deexcitation energy is carried off by a characteristic x-ray (*4*) or an Auger electron (*5*). **B**, In the ionization process, sufficient energy (*E*) is supplied to completely remove an electron from the atom (*2*). The vacancy is then filled by the deexcitation process described above. (From Freeman LM: *Freeman and Johnson's Clinical Radionuclide Imaging*, ed 3. Orlando, FL, Grune & Stratton, 1984, vol 1.)

photons whose energies are equal to the difference in binding energies of the two shells involved in the transition. They are identified on the basis of the shell in which the original vacancy existed. For example, an electron dropping down from the *L* shell to fill a vacancy in the *K* shell will result in the emission of the *K* x-ray.

Auger electron emission is an alternative to characteristic x-ray emission. In this process, the energy released by an outer-shell electron filling an inner-shell vacancy is transferred to another orbital electron, which is then ejected from the atom. The kinetic energy of this electron is equal to the binding energy of the shell being filled minus the sum of the binding energies of the two shells ending up with vacancies after the process is complete. Characteristic x-ray emission or Auger electron emission occurs after each transition. The fluorescent yield is defined for each shell of each element as the probability of characteristic x-ray emission per shell vacancy.

If sufficient energy is absorbed by an orbital electron to completely remove it from the atom, the process is termed ionization (Fig. 1.2**B**). The electron then has a kinetic energy equal to the energy absorbed minus the binding energy of the shell from which it was removed. The atom is left in an excited state and it is deexcited by outer-shell electrons dropping down to fill the vacancies, again resulting in characteristic x-ray or Auger electron emission as previously described. This process continues until the vacancy moves to the outermost shell, where a free electron is captured to return the atom to its ground state and make it electrically neutral again.

Nuclear Physics

The nucleus of an atom is composed of protons (positively charged) and neutrons (no charge), collectively termed nucleons. The most fundamental characteristic of an atom is its atomic number (*Z*), which is the number of protons within the nucleus (also the number of electrons in the electrically neutral atom). Each element therefore has a unique atomic number and thus the chemical symbol for the element is synonymous with the atomic number. The number of neutrons within the nucleus is denoted by *N*. The atomic mass number (*A*) is the total number of nucleons (neutrons + protons) within the nucleus, and thus $A = Z + N$. The atomic mass number is approximately equal to—but not to be mistaken for—the atomic weight, which is the average of the atomic mass numbers of all the naturally occurring atoms of an element weighted according to their natural percentages of abundance.

Any nucleus plus its orbital electrons (i.e., any atom) is termed a nuclide. A nuclide thus is classified on the basis of its nuclear composition and arrangement of nucleons within the nucleus. A nuclear shorthand exists for the characterization of nuclides and is of the form ${}^{A}_{Z}X_{N}$ where *X* is the chemical symbol of the element to which the nuclide belongs. Since *Z* is synomous with the chemical symbol and $N = A - Z$, the shortened form ${}^{A}X$ is generally used, as in ^{131}I ($Z = 53$, $N = 78$) and ^{57}Co ($Z = 27$, $N = 30$). Another form that is acceptable but less widely used is *X-A*, as in I-131 and Co-57.

Nuclides that have similar characteristics are often grouped into nuclear families. Isotopes are nuclides that have the same atomic number (*Z*) and thus are nuclides of a particular element. Isobars are nuclides with the same atomic mass number (*A*). Isotones are nuclides with the same number of neutrons (*N*). Isomers are nuclides that are identical in all characteristics except the energy state of the nucleus. An easy way to remember these definitions is the following: isoto*p*es have the same *p*roton number, isob*a*rs have the same *a*tomic mass number, isoto*n*es have the same *n*eutron number, and isom*e*rs differ only in *e*nergy

Table 1.2. Nuclear Families

Name	A	Z	N	Energy State	Examples
Isotope	Dif.	Same	Dif.	Dif.	^{127}Xe, ^{129}Xe, ^{131}Xe
Isobar	Same	Dif.	Dif.	Dif.	^{131}I, ^{131}Xe, ^{131}Te
Isotone	Dif.	Dif.	Same	Dif.	^{131}I, ^{132}Xe, ^{133}Cs
Isomer	Same	Same	Same	Dif.	^{99}Tc, ^{99m}Tc

state. These nuclear families, along with examples, are summarized in Table 1.2.

RADIOACTIVE DECAY

It has been observed that most nuclei existing in nature are stable. Those that are not stable transform themselves randomly and spontaneously to form more stable configurations. This transformation can result in the emission of particles or energy from the nuclei. One important factor in the stability of the nucleus is the neutron:proton ratio. Figure 1.3 shows a plot of neutron number, N, versus proton number (atomic number), Z, for the relatively stable nuclei. The stable nuclei fall along a narrow band called the line of stability. Light nuclei tend to contain the same number of neutrons and protons, and thus the slope is initially approximately unity. As Z increases, the N:Z ratio increases to about 1.5. The extra neutrons serve to increase the average distance between protons within the nucleus, thereby reducing the repulsive coulombic force acting between these particles. If the N:Z ratio deviates to either side of the line of stability due to an excess of protons or neutrons, the nuclides become unstable. Stability is achieved by emission of particles from the nucleus, resulting in a change in the identity of the nuclide and a more favorable N:Z ratio.

The process described above is termed radioactive "decay." The term was coined in the early 1900s by investigators who noted that some elements lost their radioactive properties in a consistent fashion that varied from one element to another. It was reasoned that some radioactive atoms were "disintegrating" and producing other atoms. Radioactive decay is a random and spontaneous nuclear process in which an unstable parent nucleus transforms into a more stable daughter nucleus through the emission of particles or gamma rays. Energy is also released and carried off by the radioactive emissions. The process is totally unaffected by changes in temperature, pressure, or chemical combinations. Any unstable or radioactive atom is referred to as a radionuclide. The most important factors determining stability are a favorable N:Z ratio, pairing of nucleons, and a high binding energy per nucleon. The greater the variance from these three factors, the greater the tendency of a nuclide to be unstable.

Radionuclides either occur naturally or are artificially produced. The naturally occurring radionuclides are those that exist in an unstable state in nature. They emit radiation spontaneously with no external influence necessary to produce radioactive decay. Most of the naturally occurring ra-

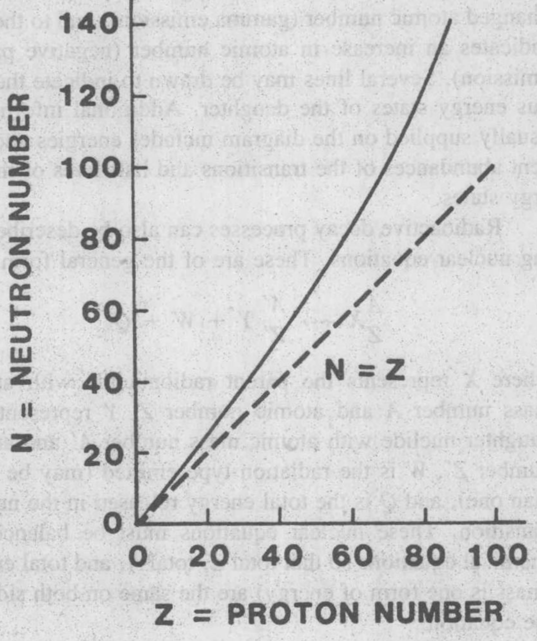

Figure 1.3. Neutron number (N) versus proton number (Z) for stable nuclei. The line of stability (*solid line*) deviates from the $N = Z$ line (*dashed line*) due to a necessary excess of neutrons. (From Freeman LM: *Freeman and Johnson's Clinical Radionuclide Imaging*, ed 3. Orlando, FL, Grune & Stratton, 1984, vol 1.)

dionuclides have atomic numbers greater than 82. Two notable exceptions are ^{14}C and ^{40}K. The artificial radionuclides are man-made unstable nuclides produced by bombarding stable nuclides with high-energy particles in a cyclotron, linear accelerator, or nuclear reactor. All of the radionuclides used in nuclear medicine fall into the latter category.

Decay Schemes

All radioactive decay processes can be described using decay schemes that present a detailed analysis of how a radioactive parent is transformed into the ground state of the daughter. Figure 1.4 illustrates the standard format used. An arrow is drawn from the parent to the daughter with the *D-U-I* mnemonic used to indicate that an arrow drawn to the left indicates a decrease in atomic number

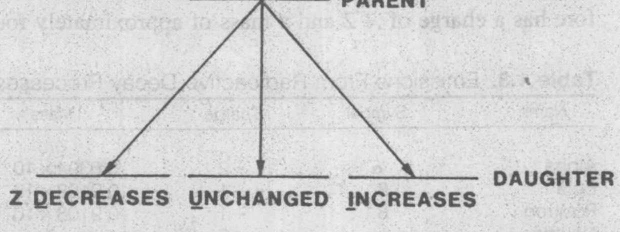

Figure 1.4. Standard format used to illustrate decay schemes. (From Freeman LM: *Freeman and Johnson's Clinical Radionuclide Imaging*, ed 3. Orlando, FL, Grune & Stratton, 1984, vol 1.)

(positive particle emission), straight down indicates unchanged atomic number (gamma emission), and to the right indicates an increase in atomic number (negative particle emission). Several lines may be drawn to indicate the various energy states of the daughter. Additional information usually supplied on the diagram includes energies and percent abundances of the transitions and half-lives of the energy states.

Radioactive decay processes can also be described using nuclear equations. These are of the general form:

$$^{A}_{Z}X \dashrightarrow {}^{A'}_{Z'}Y + W + Q$$

where X represents the parent radionuclide with atomic mass number A and atomic number Z, Y represents the daughter nuclide with atomic mass number A' and atomic number Z', W is the radiation type emitted (may be more than one), and Q is the total energy released in the nuclear transition. These nuclear equations must be balanced as chemical equations so that total Z, total A, and total energy (mass is one form of energy) are the same on both sides of the equation.

Decay Processes

There are seven basic nuclear decay processes, which may be grouped into three major categories. These are alpha transitions, isobaric transitions (including beta emission, positron emission, and electron capture), and isomeric transitions (including excited and metastable state transitions and internal conversion). The kinds of radiation emitted in these processes are summarized in Table 1.3. The transformation of a radioactive parent to the ground state of the daughter may involve one or more of these transitions. Of these seven, only six are of importance in nuclear medicine imaging. These are beta emission, positron emission, electron capture, and the isomeric transitions.

Alpha Decay

The alpha decay process may be described by the equation:

$$^{A}_{Z}X \dashrightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha + Q$$

The alpha particle (α) is the nucleus of the ^{4}He atom, which consists of two protons and two neutrons, and therefore has a charge of +2 and a mass of approximately four nucleons. Alpha particles are usually of high energy and short range (a few centimeters in air, a fraction of a millimeter in tissue) and occur primarily in nuclei with atomic numbers greater than 82. An example of alpha decay is shown in Figure 1.5 and is described by:

$$^{226}_{88}Ra \dashrightarrow {}^{222}_{86}Rn + {}^{4}_{2}\alpha$$

Because of the large size, high energy, and short range of alpha particles, their radiation dosimetry levels are very high and they cannot escape body tissues. Thus they have no use in nuclear medicine imaging procedures.

Beta Decay

Isobaric transitions are decay processes in which the parent and daughter are isobars—members of a nuclear family that have the same atomic mass number A but different Z and N. Three isobaric processes are possible: beta decay, positron decay, and electron capture. In beta emission the nuclear reaction is of the form:

$$^{A}_{Z}X \dashrightarrow {}^{A}_{Z+1}Y + \beta^- + \bar{\nu} + Q$$

The beta particles (β^-) are negatively charged electrons and therefore have the same mass as the electron. They have a broad distribution of energies, their velocities approach the speed of light, and they are classified as medium-range particles (several hundred centimeters in air, a few millimeters in tissue). Beta emission occurs in unstable nuclides that have an unfavorably high N:Z ratio due to too few protons or an excess of neutrons. Greater stability is obtained in these nuclides by the conversion of a neutron into a proton by emitting a beta particle. This conversion may be written as:

$$^{1}_{0}n \dashrightarrow {}^{1}_{1}p + \beta^- + \bar{\nu} + Q$$

It was originally thought that Q, the energy of the transition, was equal to the energy of the beta particle plus that of any associated gamma rays. However, when measurements of beta energies were made from a large number of

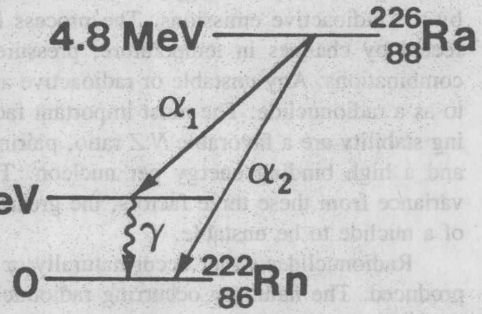

Figure 1.5. ^{226}Ra decay scheme illustrating alpha decay. (From Freeman LM: *Freeman and Johnson's Clinical Radionuclide Imaging*, ed 3. Orlando, FL, Grune & Stratton, 1984, vol 1.)

Table 1.3. Emissions From Radioactive Decay Processes

Name	Symbol	Charge	Mass
			gm
Alpha	α	+2	6.6394×10^{-24}
Beta	β^-	−1	0.9108×10^{-27}
Positron	β^+	+1	0.9108×10^{-27}
Neutrino	ν	0	0
Antineutrino	$\bar{\nu}$	0	0
Gamma	γ	0	0

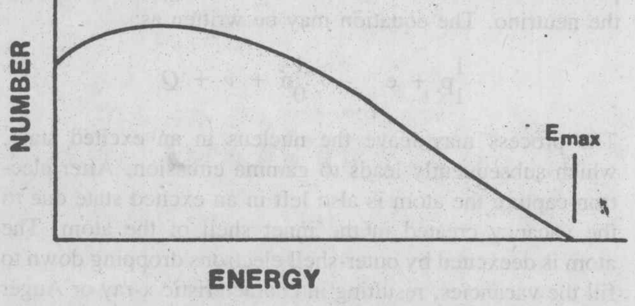

Figure 1.6. Typical spectrum of beta energies for a particular beta decay process. (From Freeman LM: *Freeman and Johnson's Clinical Radionuclide Imaging*, ed 3. Orlando, FL, Grune & Stratton, 1984, vol 1.)

atoms of a particular radionuclide, it was observed that the beta particles had a continuous range of energies from 0 to a maximum value that was equal to Q when there were no gamma rays involved in the decay process. A typical beta spectrum is shown in Figure 1.6. The average beta energy is approximately equal to one-third of the maximum energy. To explain the variance in both energies, a new particle was postulated by Pauli in 1931, and its existence was later verified experimentally. This particle, the antineutrino ($\bar{\nu}$), has no mass and no charge and is the antiparticle of the beta particle. It carries off the excess energy in each beta decay process ($E_{max} = E_{\beta-} + E_{\bar{\nu}}$). In some nuclides, after beta decay the nucleus may be left in an excited state, resulting in gamma emission to carry away the excess nuclear energy.

An example of beta decay is the transformation of ^{131}I to ^{131}Xe by the nuclear equation:

$$^{131}_{53}\text{I} \longrightarrow \, ^{131}_{54}\text{Xe} + \beta^- + \bar{\nu}$$

The corresponding decay scheme is shown in Figure 1.7.

Positron Decay

Positron emission is a second type of isobaric transition. In this decay process unstable nuclides that have an unfavorably low N:Z ratio, either because of an excess of protons or a deficiency of neutrons, are transferred to a more stable configuration through the nuclear equation:

$$^{A}_{Z}X \longrightarrow \, ^{A}_{Z-1}Y + \beta^+ + \nu + Q$$

The positron (β^+) has the same mass as the electron but is positively charged. The decay process may be described by the conversion of a proton to a neutron with the emission of a positron as indicated by:

$$^{1}_{1}\text{p} \longrightarrow \, ^{1}_{0}\text{n} + \beta^+ + \nu + Q$$

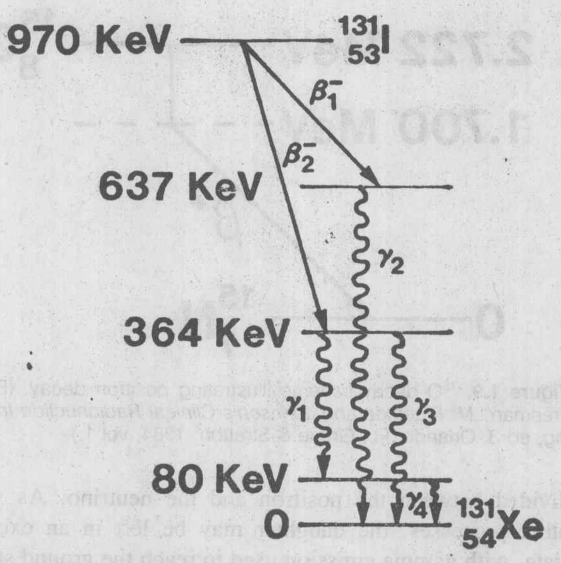

Figure 1.7. ^{131}I decay scheme illustrating beta decay. (From Freeman and Johnson's Clinical Radionuclide Imaging, ed 3. Orlando, FL, Grune & Stratton, 1984.)

Although this reaction appears impossible because the mass of the neutron is greater than the mass of the proton, the equation describes the restructuring of the nucleus and, therefore, it is assumed that the energy necessary to form the neutron is supplied by the other nucleons. Positrons decay with a continuous spectrum of energies, as with beta decay, and the excess energy between the expected energy, E_{max}, and the observed energy in each decay process is carried off by the neutrino (ν), the antiparticle of the positron.

A unique characteristic of the positron is that it cannot exist at rest in nature. Once it loses its kinetic energy, it combines with a negatively charged electron and undergoes an annihilation reaction in which the masses of the two particles are converted into energy in the form of two 0.511-meV gamma rays or annihilation photons, which leave their production site at 180° from each other (Fig. 1.8). There is a minimum energy of 1.022 meV that must exist between the parent and the daughter before positron emission can occur. The excess energy above that value is

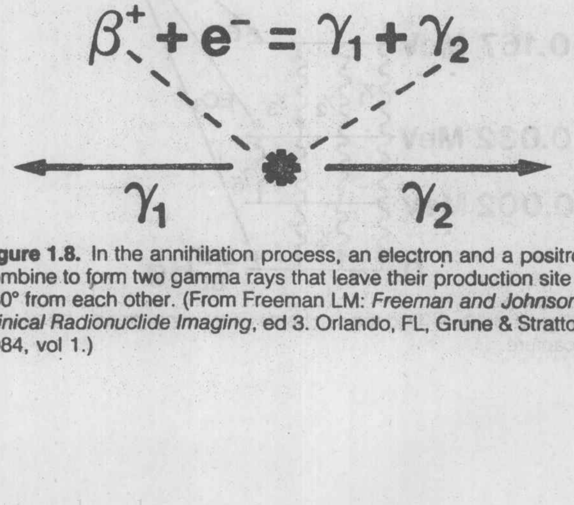

Figure 1.8. In the annihilation process, an electron and a positron combine to form two gamma rays that leave their production site at 180° from each other. (From Freeman LM: *Freeman and Johnson's Clinical Radionuclide Imaging*, ed 3. Orlando, FL, Grune & Stratton, 1984, vol 1.)