RADIOISOTOPES

1. Introduction

A radioisotope is a nuclide whose nucleus is unstable and spontaneously decays to a more stable state by the emission of various radiations. Some radioisotopes occur naturally, but most must be synthesized from stable isotopes, typically via nuclear reactions resulting from bombardment by neutrons from a nuclear reactor or charged-particle beams from a particle accelerator, such as a cyclotron. Radioactive isotopes, also called radionuclides, are important in many areas of scientific research, as well as in medicine, commerce, and industry (see RADIOACTIVE ELEMENTS; RADIOPHARMACEUTICALS).

Detailed knowledge of the radiations from each radioisotope is important because, as the uses of radioisotopes have expanded, it has become necessary to develop sensitive and accurate methods designed to identify and quantitatively measure their presence. Such measurements can determine, eg, the amount of radiation exposure of the human body or how much of the isotope is present in various places in the environment. For a discussion of detection methods used see Refs. 1 and 2.

2. History

In 1895, Roentgen observed that penetrating radiation was produced by his Crookes tube, a device in which electrons were accelerated and then stopped in a target. Unlike visible light, this radiation passed through paper (qv), wood (qv), and even thin metal sheets. The name X-rays was applied to it because the nature of the radiation was unknown, and that name has persisted for >100 years. This new phenomenon caused great excitement among scientists and the general public. Members of the medical profession immediately made use of it to study broken or malformed bone structures of their patients, as well as to attempt to treat tumors and other medical problems. It soon became clear that X-rays were also useful in industry to determine the internal structure of manufactured items. There was great fascination with this radiation, as, eg, in the entirely novel ability to observe one's own bone structure (see X-RAY TECHNOLOGY).

Hazards were discovered by experience. It was soon found that X-rays produced skin burns and lesions that healed only slowly; later it was learned that they could also produce tumors. Within the medical community, it became clear that guidelines were needed for the use of X-rays, especially for medical workers, who were often present while the X-rays were produced.

In 1896, only a few months after Roentgen announced the observation of X-rays, Becquerel reported the additional observation of penetrating radiation emitted from certain natural materials, a phenomenon that Marie Curie would later name radioactivity. This phenomenon had a much less glamorous development. Over a 3-year period, Becquerel published three articles, decided there was little else to learn about it, and went on to the study of other fields. During this period, only a few other articles were published on radioactivity and radioisotopes, but hundreds of articles were published on X-rays.

The uranium ores from which this new radiation was discovered were fluorescent, and X-ray tubes fluoresced; thus, an early hypothesis was that the visible fluorescence and the new penetrating radiation were related and would occur together. Becquerel did a series of careful experiments showing that penetrating radiation also came from some materials that did not fluoresce.

There were two immediate questions to be investigated concerning this radioactivity. The first question, about the nature of the radiation, was mainly a physics problem; the second, from whence did the radiation come, was addressed by chemical methods. Ernest Rutherford and associates led the physics studies with the early discovery of two types of rays, called alpha (α) and beta (β). These were easily distinguished by the fact that the α-rays were stopped by paper or a thin foil, whereas the β-rays were more penetrating. In 1900, Paul Villard discovered the presence of an even more penetrating radiation, called gamma (γ)-rays. In the early chemical studies of radioactivity, the α-rays were very useful for measuring the amount of radioactive material present because these produced a strong response in the ionization detectors in use at that time. The more penetrating β-rays were easily studied. In 1899 their direction of deflection in a magnetic field was observed, indicating negative charge. Then Becquerel was able to deflect β-rays in electric and magnetic fields and thereby determine their charge/mass ratio. This ratio showed that the mass was much smaller than that of any atom and corresponded to that of electrons.

In 1903, Rutherford and associates were finally able to deflect the α-rays by electric and magnetic fields, showing that these are positively charged. Measurement of the charge/mass ratio indicated that α-rays were of atomic dimensions. In 1908, definitive experiments showed α-rays to be doubly charged helium atoms, ie, helium nuclei.

The nature of γ-rays, basically the same as X-rays, was only slowly determined. Crystal diffraction had been used to show that X-rays are part of the electromagnetic spectrum and to measure their wavelengths. Because γ-rays are generally of much higher energy, ie, shorter wavelength, it was necessary to improve the crystal diffraction method before it could be used in 1913 to show that γ-rays are also electromagnetic radiation. The relationship of the X- and γ-rays to the other regions of electromagnetic radiation is illustrated in Figure 1. In some portions of the spectrum it is useful to discuss radiation in terms of its continuous wave properties of frequency and wavelength. For γ- and X-rays, however, it is usually more useful to use the discrete photon properties, such as the energy of a single photon. An energy of 1-eV corresponds to a wavelength of 1.24×10^{-6} m or a frequency of $2.42 \times 10^{+14}$ Hz.

It was shown early on that uranium and thorium are radioactive, independent of their chemical and physical form. At the same time, it was shown that some ores had more activity than others for a given amount of uranium. Starting with knowledge that the mineral pitchblende has a higher specific radioactivity, defined as the activity per unit mass as exemplified by the rate of discharge of ionization detectors per gram of material, than other uranium ores, Marie Curie chemically processed tons of the ore in order to extract portions having different chemical properties. She and her associates were able to extract a fraction that was chemically similar to bismuth, to be named polonium, and another fraction that was chemically like barium, to be called radium. From repeated purification

steps, she was able to produce a very pure radium fraction that had 10^6 times the specific radioactivity of uranium and, from optical spectrometry, others were able to show that her samples were essentially pure radium. Measurement of the atomic mass as ~225 gave the first proof that radium was not a new form of barium, which has a mass of ~ 137, but rather a new element having a mass between that of lead (qv) and uranium (see URANIUM AND URANIUM COMPOUNDS).

The same chemical separation research was done on thorium ores, leading to the discovery of a completely different set of radioactivities. Although the chemists made fundamental distinctions among the radioactivities based on chemical properties, it was often simpler to distinguish the radiation by the rate at which the radioactivity decayed. For uranium and thorium, the level of radioactivity was independent of time. For most of the radioactivities separated from these elements, however, the activity showed an observable decrease with time and it was found that the rate of decrease was characteristic of each radioactive species. Each species had a unique half-life, ie, the time taken for the activity to decrease to one-half of its initial value.

By this time, the Periodic Table of elements was well developed, although it was considered a function of the atomic mass rather than the atomic number. Before the discovery of radioactivity, it had been established that each natural element had a unique mass, so it was assumed that each element was made up of only one type of atom. Some of the radioactivities found in both the uranium and thorium decays had similar chemical properties but, because these had different half-lives, it was assumed that they arose from different elements. It was soon realized, however, that if all the different radioactivities from uranium and thorium were separate elements, there would be too many elements to fit into the Periodic Table.

To resolve this problem, two concepts needed to be developed. The first, accepted in 1910, was that in α and β decay the original element is transmuted into a different element. The second concept was that for each element there can be atoms having different nuclear properties. These were first called isotopes in 1913. Using these concepts, the various natural decay chains began to fall into place. The uranium and thorium chains are shown in Tables 1 and 2. Although early researchers had reason to believe that only elements above Pb in the Periodic Table were radioactive, the development of far more sensitive measurement methods has shown that natural radioactivity exists throughout the Periodic Table. Natural radioisotopes, excluding the actinides (see ACTINIDES AND TRANSACTINIDES), are listed in Table 3.

The subsequent study of radioactive isotopes revealed much basic information about the forces of Nature. Prior to the twentieth century, the gravitational force that exists between bodies having mass and the electromagnetic force that causes charged or magnetic bodies to attract or repel each other were known. Studies of radioactive decay have led to the understanding of two more forces: the strong force between protons and neutrons that holds nuclei together; and the weak force, responsible for radioactive decay by the β-decay process. Advances in knowledge continue in several areas, including studies of the rare decay modes of double β-decay and cluster emission.

3. Nuclear Physics Properties

3.1. The Atom. Before the studies by Rutherford, several models of the atom were proposed. It was clear that atoms contained electrons because these could be extracted from the atoms. In order to have the whole atom be electrically neutral, it had to contain an equal amount of positive charge. Because the only forces known at that time were gravity and electromagnetism, atomic models had to be carefully contrived to achieve an assembly of positive and negative charges that would stay together. Based on the observed scattering of α-particles from thin metal foils, it was deduced that almost all of the mass of the atom along with the positive charge was concentrated in a very small volume called the nucleus. This nucleus has a diameter of $\sim 10^{-12}$ cm, compared with $\sim 10^{-8}$ cm for that of an atom. It has been found that for all isotopes the diameter of the nucleus is $\sim 2.4 \times 10^{-13} A^{1/3}$ cm, where A is the atomic mass. This corresponds to a density of the order of 10^{14} g/cm^3. The space outside the nucleus, which is almost all of the atom's volume, is occupied by a cloud of electrons.

This model had an immediate nuclear problem because the positive charges in the nucleus will repel each other and the nucleus should, therefore, blow itself apart. The model clearly required a new force to hold the particles in the nucleus together.

At the same time, the laws of classical electromagnetism suggested the opposite problem for the atom as a whole, owing to the attraction between the positively charged nucleus and the negatively charged electrons in the cloud. Unless the electrons were in rapid motion around the nucleus, they would fall directly into the nucleus, whereas, if the electrons were in such motion, classical electromagnetism required that they radiate energy (called bremsstrahlung), thereby losing energy and spiralling into the nucleus. In either case, the atom should collapse into the size of the nucleus. Therefore, some new laws of physics were needed to go along with the new nuclear force.

In 1913, Niels Bohr proposed a system of rules that defined a specific set of discrete orbits for the electrons of an atom with a given atomic number. These rules required the electrons to exist only in these orbits, so that they did not radiate energy continuously as in classical electromagnetism. This model was extended first by Sommerfeld and then by Goudsmit and Uhlenbeck. In 1925, Heisenberg, and in 1926, Schrödinger, proposed a matrix or wave-mechanics theory that has developed into quantum mechanics, in which all of these properties are included. In this theory, the state of the electron is described by a wave function from which the electron's properties can be deduced.

The structure of the particles inside the nucleus was the next question to be addressed. One step in this direction was the discovery of the neutron in 1932 by Chadwick, and the determination that the nucleus was made up of positively charged protons and uncharged neutrons. The number of protons in the nucleus is known as the atomic number, Z. The number of neutrons is denoted by N, and the atomic mass is thus $A = Z + N$. Another step toward describing the particles inside the nucleus was the introduction of two new forces, namely, the strong force that holds the protons and neutrons together in spite of the repulsion between the positive charges of the protons, and the weak force that produces the transmutation by β-decay.

The theory of quantum mechanics requires that nuclear states have discrete energies. This is in contrast to classical mechanical systems, which can have any one of a continuous range of energies. This difference is a critical fact in the applications of radioactivity measurements, where the specific energies of radiations are generally used to identify the origin of the radiation. Quantum mechanics also shows that there are other quantities that have only specific discrete values, and the whole understanding of atomic and nuclear systems depends on these discrete quantities.

3.2. Conservation of Energy. Because the naturally occurring radioactive materials continued to emit particles, and thus the associated energy, without any decrease in intensity, the question of the source of this energy arose. Whereas the conservation of energy was already a firmly established law of physics, the origin of the energy in the radioactivity was unknown. Its source became clear using the postulate of Einstein that mass can be converted to energy, and vice versa, once knowledge of the nuclear masses involved became available. The specific relationship is $E = mc^2$, where E is the equivalent energy, m is the mass, and c is the velocity of light. This conservation law was challenged when the β-decay process was first studied, but it was finally shown that all types of radioactive decay result in a state of lower energy for the emitting atom and nucleus.

3.3. Angular Momentum and Parity. Another set of properties of each atomic and nuclear state and the associated radiations are the parity and the angular momentum, or spin. These are quantum mechanical properties, the origins of which are not discussed here in detail, but their phenomenological results are important. The parity, which depends on the reflection symmetry of the wave function, is designated by π and is either + or− (or + 1 or −1) for any state. The spin or angular momentum is a vector quantity denoted by $\boldsymbol{J}$ for an atomic or nuclear level and by $\boldsymbol{L}$ for a γ-ray or other radiation. The lengths of these vectors, or the maximum component in any direction, are $| J(J+1)^{1/2}\hbar |$ and $| L(L+1)^{1/2}\hbar |$, where $\hbar = h/2\pi$ and $h =$ Planck's constant. The usual practice is to simply denote the length of $\boldsymbol{J}$ and $\boldsymbol{L}$ by J and L.

For any nuclear decay, such as the emission of a γ-ray, the angular momentum and parity must be conserved. Therefore, if $\boldsymbol{J}_i$, π_i and $\boldsymbol{J}_f$, π_f are the spins and parities of the initial and final levels, and $\boldsymbol{L}$ and π_γ are the angular momentum and parity carried off by the γ-ray,

$$\mathbf{J}_i = \mathbf{J}_f + \mathbf{L}$$

and

$$\pi_i = \pi_f \pi_\gamma$$

In terms of the magnitudes of the spin vectors, this means that

$$\left| J_f - L \right| \leq J_i \leq J_f + L$$

These rules have very distinct influences on the decays of nuclear states.

3.4. Properties of Particles. From research during the early part of the twentieth century, the existence of several types of particles was firmly established, and their properties were determined. The particles that are involved in the decay of radioisotopes are listed in Table 4. An additional type of conservation law is that in all atomic and nuclear decays, the number of nucleons, ie, protons and neutrons, is conserved and the number of leptons, ie, electrons and neutrinos, is conserved also.

Another consequence of the quantum theory of the atomic and nuclear systems is that no two particles can have exactly the same wave function. The practical significance of this rule is that only a specific number of particles can occupy any particular atomic or nuclear level. This prevents all of the electrons of the atom, or protons and neutrons in the nucleus, from deexciting to the single lowest energy state.

3.5. Half-Lives and Decay Constants. Each nuclear state, whether an unstable ground or an excited state, has a characteristic probability of decay per unit time λ, which is known as the decay constant. For a level that decays by more than one mode, each mode has a partial decay constant λ_i, such that $\lambda=\Sigma_i\lambda_i$.

Very early in the study of radioactivity it was determined that different isotopes had different λ values. Because the laws of gravity and electromagnetism were deterministic, an initial concept was that, when each radioactive atom was created, its lifetime was determined, but that different atoms were created having different lifetimes. Furthermore, these different lifetimes were created such that a collection of nuclei decayed in the observed manner. Later, as the probabilistic properties of quantum mechanics came to be accepted, it was recognized that each nucleus of a given radioactive species had the same probability for decay per unit time and that the randomness of the decays led to the observed decay pattern.

Experimental measurements have shown that the following description of the decay is correct. If at any time t there is a large number of nuclei, $N(t)$, all in a state that has the decay constant λ, then the change in the number of nuclei in this state in a short time interval dt is

$$dN = -\lambda N(t)dt$$

If N_0 is the number of nuclei in this state at time $t=0$, then the number of nuclei in this state at any later time t is

$$N(t) = N_0 e^{-\lambda t}$$

and the associated activity, or the decay rate, is

$$A(t) = |dN/dt| = \lambda N(t) = \lambda N_0 e^{-\lambda t}$$

For the N_0 nuclei that exist at $t = 0$, the average or mean life τ is given by the sum of the times of existence for all the atoms divided by N_0. Thus, for large N_0,

$$\tau = -\frac{1}{N_0}\int_0^\infty t dN = \frac{1}{N_0}\int_0^\infty t\lambda N(t)dt = \int_0^\infty t\lambda e^{-\lambda t}dt = -\left[\frac{\lambda t + 1}{\lambda}e^{-\lambda t}\right]_0^\infty = \frac{1}{\lambda}$$

Usually, in a description of nuclear properties, the half-life $t_{1/2}$ is quoted rather than the decay constant. This quantity is the time it takes for one-half of the original nuclei to decay. That is,

$$N(t_{1/2}) = N_0/2 = N_0 e^{-\lambda t_{1/2}}$$

which has the solution $t_{1/2} = (\ln 2)/\lambda$.

At any time t during this decay process the number of daughter nuclei, D, will be increasing at the same rate as the number of parent nuclei is decreasing. So,

$$dD(t)/dt = +\lambda N(t) = +\lambda N_0 e^{-\lambda t}$$

If, at $t = 0$, there were no daughter atoms, then at time t,

$$D(t) = N_0(1 - e^{-\lambda t})$$

and, for t very large, essentially all of the original radioactive atoms will have been converted to daughter atoms.

In almost all cases, λ is unaffected by any changes in the physical and chemical conditions of the radionuclide. However, there are special conditions that can influence λ. An example is the decay of ^{7}Be, which occurs via the capture of an atomic electron by the nucleus. Chemical compounds are formed by interactions between the outer electrons of the atoms in the compound, and different compounds have different electron wave functions for these outer electrons. Because ^{7}Be has only four electrons, the wave functions of the electrons involved in the electron-capture process are influenced by the chemical bonding. The change in the ^{7}Be decay constant for different compounds has been measured, and the maximum observed change is $\sim 0.2\%$.

For any nuclide that decays only by this electron-capture process, the effective $t_{1/2}$ would become infinite if one were to produce an atom in which all of the electrons were removed. An interesting example of this involves the decay of ^{54}Mn in interstellar space. When surrounded by its normal electron cloud, ^{54}Mn decays with a half-life of 312 days and this decay takes place by electron capture $> 99.99\%$ of the time. The remaining decays are $(1.20 \pm 0.26) \times 10^{-7}\%$ by β^+ emission (7) and $\sim 6 \times 10^{-5}\%$ by β^- emission (8). In interstellar space, some ^{54}Mn atoms would have all of their electrons stripped off so they could

only decay by β^- or β^+ emission and, therefore, their effective half-life would increased dramatically to $\sim 1.5 \times 10^6$ year.

Despite these special cases, the decay constants and half-lives of nuclides can be considered to be independent of the physical and chemical environment in all applied uses.

The above decay equations apply to the simple case of a radionuclide that is decaying without being replenished. There are many cases in which some nuclear species is being produced at the same time as it is decaying. One common example of this would be the case where one radioactive nuclide is produced by the decay of another nuclide (see Tables 1 and 2). If, at time $t = 0$, there are $N_1(0)$ atoms of nuclide 1 (the parent) having decay constant λ_1, and $N_2(0)$ atoms of nuclide 2 (the daughter of nuclide 1's decay), having decay constant λ_2, then

$$\frac{dN_1(t)}{dt} = -\lambda_1 N_1(t)$$

and

$$\frac{dN_2(t)}{dt} = +\lambda_1 N_1(t) - \lambda_2 N_2(t)$$

The solutions to these equations give the number of atoms of each nuclide that are present at time t as

$$N_1(t) = N_1(0)e^{-\lambda_1 t}$$

and

$$N_2(t) = N_2(0)e^{-\lambda_2 t} + [N_1(0)\lambda_1/(\lambda_2 - \lambda_1)](e^{-\lambda_1 t} - e^{-\lambda_2 t})$$

The respective activities, A, of the two nuclides are then

$$A_1(t) = \lambda_1 N_1(0)e^{-\lambda_1 t}$$

and

$$A_2(t) = \lambda_2 N_2(t) = \lambda_2 N_2(0)e^{-\lambda_2 t} + [N_1(0)\lambda_2\lambda_1/(\lambda_2 - \lambda_1)](e^{-\lambda_1 t} - e^{-\lambda_2 t})$$

If one has a sample that contains only the parent at $t = 0$, and the parent half-life is much longer than that of the daughter ($\lambda_1 << \lambda_2$), the daughter activity grows exponentially, and then decreases as the parent decays. At values of t that are large compared to the daughter half-life, the activities reach a constant ratio and the daughter activity is larger than that of the parent by the ratio $\lambda_2/(\lambda_2 - \lambda_1)$. This situation is called transient equilibrium. However, if the parent and daughter

half-lives are comparable, the ratio of the activities does not establish a useful equilibrium. If, instead, the parent half-life is much shorter than that of the daughter ($\lambda_1 >> \lambda_2$), the initially short-lived sample ultimately becomes a long-lived sample of just the daughter nuclei.

If there are more than two members of the decay sequence, as for the natural chains from ^{238}U and ^{232}Th in Tables 2 and 3, the activity of each member depends on the initial abundances and the half-lives of all of the previous members.

3.6. Atomic Levels and Their Decay. There are many commonalities between the properties of atomic and nuclear levels and their respective decays. Each level has a quantum mechanical wave function that describes its properties. It is common practice to illustrate the atomic and nuclear information in terms of level diagrams.

The levels in which the individual atomic electrons reside are illustrated in Figure 2**a** for an atom of nickel, Ni, in its ground state. Atomic levels are commonly grouped by energy. The lowest energy, most tightly bound level is labeled K; the next group of three closely spaced levels is labeled L_i; etc. If energy from some external source is transferred to one of the two K-shell electrons, the electron could be excited to a higher energy state, or it could be completely removed from the atom, as illustrated in Figure 2**b**. The complete removal of an electron from shell X is referred to as ionization in the X shell. In either case, the atom will no longer be in the ground state and will promptly return to a lower energy state by having an outer electron transfer to the K shell. The vacancy that this creates in an outer shell will then be filled by another electron from a still higher energy level, etc. If the original excitation completely removes the K-shell electron, the atom must attract an electron from the surrounding material if it is to become electrically neutral and return to its ground state. This process is illustrated in Figure 2**c** by the emission of three consecutive X-rays.

The electrons in each atomic level have specific spins or angular momenta and parities. These properties define the characteristics of the level and the X-ray spectrum produced. Figure 3 illustrates a typical X-ray spectrum where the four peaks above channel 1400 arise from the filling of a hole in the K shell by electrons from the L subshells, tagged by K_α, and from the higher lying shells, tagged by K_β. Once a single hole is created in the K shell, the energies and intensities of these four peaks are completely determined by the wave functions of the atomic electrons and not by the mode of excitation of the K-shell electron. The spin and parity of the electrons in the L_2 and L_3 subshells allow these electrons to fill the K-shell hole, but the spin of the electrons in the L_1 subshell make it very unlikely for them to fill a K-shell hole. The K_α region in Figure 3, therefore, has two peaks, not three.

4. Modes of Nuclear Decay and Associated Radiations

The decay of radioisotopes involves both the decay modes of the nucleus and the associated radiations that are emitted from the nucleus. In addition, the resulting excitation of the atomic electrons, the deexcitation of the atom, and the radiations associated with these processes all play a role. Some of the atomic

processes, such as the emission of K X-rays, are inherently independent of the nuclear processes that cause them. There are others, such as internal conversion, where nuclear and atomic processes are closely related.

There are four modes of radioactive decay that are common and that are exhibited by the decay of both naturally occurring and synthetic radionuclides. These four are isomeric or γ-decay, β-decay, electron capture and β^+-decay, and α-decay. In the first of these, the element is unchanged; in the latter three, the atom is changed from one chemical element to another. In addition, there are three modes of decay that occur almost exclusively in synthetic radionuclides. These are spontaneous fission, delayed-proton emission, and delayed-neutron emission. Finally, there are two exotic, and very long-lived, decay modes. These are cluster emission and double β-decay. In all of these processes, the energy, spin and parity, nucleon number, and lepton number are conserved. Methods of measuring the associated radiations are discussed in Ref. 2; specific methods for γ-rays are discussed in Ref. 1.

4.1. β^--Decay. In this type of decay, a β^--particle is emitted from the nucleus and the parent atom with Z and A is transmuted into a daughter atom with $Z+1$ and A. The emitted β-particle is an ordinary electron having the properties listed in Table 4. This decay mode is equivalent to converting a neutron into a proton. There can be β^- branches to the different levels in the daughter nucleus. If this decay were analogous to α-decay, it would result in a series of monoenergetic electron groups corresponding to the daughter levels. However, early experiments showed that these electrons had a continuous energy spectrum. This could be interpreted to mean either that the decay involved one or more unidentified particles, or that energy was not conserved.

Pauli proposed that two particles were emitted, and Fermi called the second one a neutrino, ν. The complete process therefore is $n \rightarrow p + e^- + \bar{\nu}$. Owing to the low probability of it interacting with other particles, the neutrino was not observed until 1959. Before the β^--decay takes place there are no free leptons, so the conservation of leptons requires that there be a net of zero leptons afterward. Therefore, the associated neutrino is designated an antineutrino, $\bar{\nu}$, ie, the emitted electron (lepton) and antineutrino (antilepton) cancel and give a net of zero leptons.

The decay energy is shared between the electron and the antineutrino, and each particle has an energy distribution that extends from 0 to the total energy available, namely, $Q - E_D$, where E_D is the excitation energy of the level fed. The β-decay theory, developed by Fermi, provides a prediction of the energy distribution of the electrons from various classifications of β^--decays, and these predictions have been verified experimentally. The β^--decays are classified by the change in nuclear spin and parity as indicated in Table 5. The specific probability for β^--decay to each of the levels of the daughter nucleus depends on the individual wave functions for the levels involved. However, the probability also decreases rapidly as the available energy decreases, as well as by the factors shown in Table 5 for the various classifications. Thus, the strongest β^- branches are typically those to levels near the ground state of the daughter nucleus, which involve the smallest spin and parity changes between the parent and daughter levels.

The masses of the neutrinos have traditionally been considered to be exactly 0, but modern theory and recent experiments suggest nonzero masses, probably < 1 eV. Because the neutrinos have such a small mass and no electrical charge, they interact primarily via the weak interaction. This means that their interaction probability is very small and they typically pass through a mass as great as the earth's without interacting. Therefore, they are not useful for any measurements related to radioactive decay.

4.2. Electron Capture and β^+-Decay. These processes are essentially the inverse of β^--decay in that the parent atom having Z and A transmutes into one having $Z-1$ and A. This mode of decay occurs via the capture of an atomic electron by the nucleus, thereby converting a proton into a neutron. The loss of one lepton (the electron) requires the creation of another lepton (a neutrino) that carries off the excess energy, namely, $Q-E_D-E(e^-)$, where the last term is the energy by which the electron was bound to the atom before it was captured. So the process is equivalent to $p + e^- \rightarrow n + \nu$. The experimental signature for this process is the emission of X-rays from the atom as the resulting hole in an atomic shell is filled. If the decay energy to the level is well above the binding energy of the K electrons, the capture occurs from all atomic shells, but it is primarily from the K shell. If the decay energy to a level is below the K-shell binding energy, then capture only occurs from the higher atomic shells. The relative probability of capturing an electron from a specific atomic shell can be calculated theoretically, and some examples for the K and L shells are given in Table 6.

In this process, only one particle is emitted, so the energy spectrum of the neutrinos consists of discrete lines and, in principle, the energies of the levels in the daughter nucleus could be determined from this spectrum. However, the detection of neutrinos is very difficult, so this is not a practical possibility.

The same transmutation can also occur by positron, or β^+, emission , in which the process is $p \rightarrow n + \beta^+ + \nu$. As in β^--decay, the β^+ and ν share the available energy of $Q-E_D - 2m_0c^2$, where m_0c^2 is the energy equivalent of the mass of an electron, or 511.0 keV. The $2m_0c^2$ term occurs because the conversion of the proton into a neutron effectively requires the creation of an electron, in addition to the positron that is created. The β^+-particle is the antiparticle of the electron having the properties listed in Table 4. Because the β^+ is an antilepton and the associated neutrino is a lepton, leptons are conserved. As in the case of β^- emission, the energy distribution of the β^+ for decay to any level is continuous from 0 to the available energy and the probability of this decay to each of the daughter levels depends on the available energy, the spins, and the parities. If the decay energy is >1022 keV, both electron capture and β^+-decay can occur to a level and the relative probabilities of the two can be calculated from the β-decay theory. Some examples of the theoretical electron-capture/β^+ ratios are included in Table 6.

4.3. γ-Decay. In the γ-decay mode, a nucleus in an excited state decays to a lower energy state via the emission of a γ-ray, and the values of Z and A are unchanged. Although, to first order, the γ-ray carries off all of the available energy, a small amount of energy will in fact be transferred to the atom, which recoils with an energy of $E_r = 0.5368 \times 10^{-6} E^2{}_\gamma / A$, where A is the atomic mass and E_γ is the γ-ray energy; both energies are in keV. An isomeric transition

or isomeric decay is a γ-ray transition from a nuclear state that has a significantly long half-life, eg, longer than 1 μs.

Typically, γ-rays of interest in nuclear transitions have energies from $\sim$50 to 2500 keV, but some may be as low as 0.003 keV, which is near the visible light region (see Fig. 1), and as high as 12,000 keV. Extraterrestrial photons have been observed with energies up to 10^{18} keV. As for all electromagnetic radiation, a γ-ray has electric and magnetic properties that are indicated by their character or multipolarity, commonly designated as E1, E2, E3, E4, M1, M2, M3, or M4, etc. Here, E and M indicate electric and magnetic character and the number refers to the multipole order of the γ-ray, where 1 indicates a dipole, 2 a quadrupole, 3 an octupole, and 4 a hexadecapole transition. This number also indicates the units of angular momentum, L, carried off by the γ-ray. The transitions that do not involve a change in the parity are M1, E2, M3, and E4; the others do involve a parity change. In many cases, the character of a γ-ray is essentially of a single type, but in other cases it can be made up of a mixture of two, or even three, types. Parity conservation means that these multicomponent mixtures are of the type M1 + E2, E3 + M2, etc.

Using specific models of the nucleus, it is possible to compute theoretical wave functions for the nuclear states. For a model that assumes that the nucleus is spherical, the general properties of these wave functions have been used to compute theoretical estimates of the half-lives for γ-rays of the various multipolarities. Some values from the Weisskopf estimate of these half-lives are shown in Table 7. These half-lives decrease rapidly with the γ-ray energy, namely, as E_γ^{2L+1} and, as Table 7 shows, increase rapidly with L. This theoretical half-life applies only to the γ-ray decay, so if there are other modes of decay of the associated level, such as another γ-ray or internal conversion, the observed half-life of a level is expected to be shorter than this.

Alternatives to γ-Ray Emission. γ-Ray emission results in the deexcitation of an excited nuclear state to a lower energy state in the same nuclide, ie, it does not change Z or A. There are two other processes by which the same end result could be achieved without the emission of a γ-ray. These are internal conversion and internal pair formation. The internal-conversion process involves the transfer of the available energy to an atomic electron, so it is a combined nuclear and atomic process (discussed later).

The process of internal-pair formation occurs only rarely. It provides a good demonstration of the equivalence of mass and energy as proposed by Einstein. For γ transitions whose energy is < 1022 keV, this process cannot occur; but for higher energy transitions, a small fraction of the decays can occur by the creation of an electron–positron pair. Of the available energy, 1022 keV is used to create the two particles, and the remainder appears as kinetic energy of the two particles. The probability of the internal-pair formation (IPF) is given by the ratio of the number of pairs emitted to the number of γ-rays emitted. Table 8 gives the theoretical ratios for a few γ-ray energies, multipolarities, and atomic numbers. These IPF coefficients (IPFC) increase with E_γ, in contrast to internal-conversion coefficients, which decrease with increasing energy. From the small size of the ratios, it is clear that this effect is generally not important. However, it is of interest in very precise computations of some γ-ray emission probabilities and in the study of this effect itself. One case where the values are important is

the calculation of the γ-ray emission probabilities for the decay of ^{24}Na, as shown in Table 9, where these coefficients are larger than the corresponding internal conversion coefficients. In contrast, for ^{60}Co these coefficients are smaller than the internal-conversion coefficients, and are therefore much less significant.

4.4. Decay Schemes. For nuclear cases, it is more useful to show energy levels that represent the state of the whole nucleus, rather than energy levels for individual atomic electrons (see Fig. 2). This different approach is necessary because in the atomic case the forces are known precisely, so the computed wave functions are quite accurate for each particle. For the nucleus, the forces are much more complex and it is not reasonable to expect to be able to calculate the wave functions accurately for each particle. Consequently, nuclear decay schemes show the experimental levels rather than calculated ones. This is illustrated in Figure 4, which gives the decay scheme for ^{60}Co. Here, the lowest level represents the ground state of the whole nucleus and each level above that represents a different excited state of the nucleus.

The ^{60}Co nucleus decays with a half-life of 5.27 years by β^- emission to the levels in ^{60}Ni. These levels then deexcite to the ground state of ^{60}Ni by the emission of one or more γ-rays. The spins and parities of these levels are known from a variety of measurements and require that the two strong γ-rays of 1173 and 1332 keV both have E2 character, although the 1173 γ-ray could contain some admixture of M3. However, from the theoretical lifetime shown in Table 7, the E2 contribution is expected to have a much shorter half-life and, consequently, it should dominate in this decay. Although the emission probabilities of the strong 1173- and 1332-keV γ-rays are so nearly equal that the difference cannot be determined by a direct measurement, measurements of other parameters of the decay establish that the 1332 is the stronger. Specifically, measurements of the continuous electron spectrum from the β^--decay have shown that there is a branch of 0.12% to the 1332-keV level. When this, the weak γ-rays, the internal conversion, and the internal-pair formation are all taken into account, the relative emission probabilities of the two strong γ-rays can be determined very accurately, as shown in Table 9.

A decay scheme for ^{131}I is shown in Figure 5. The low lying states of the ^{131}Xe daughter have widely varying spins and parities, from $1/2^+$ to $11/2^-$, resulting in a variety of multipolarities for the γ-rays. The half-life of the 341-keV level is 1.6×10^{-9} s and that of the 164-keV level is 11.8 days. This large range results from the strong dependence of the γ-ray lifetime on the γ-multipolarity. Specifically, a half-life of ns for the M1 + E2 γ-ray of 177 keV and of Ms for the 164-keV M4 γ-ray. ^{131}I is often of interest both in medical diagnostics and as a monitor for release of fission products from a nuclear reactor. In these applications, it may be important to take into account the fact that the parent has a half-life of 8 days, while the half-life of the 164-keV level is 12 days. Therefore, the latter γ-ray is not in equilibrium with the parent.

4.5. Delayed Proton and Neutron Decays. By means of a variety of nuclear reactions, as well as the spontaneous fission of synthetic nuclides, large numbers of isotopes of some elements have been produced. For example, whereas the only stable isotope of Cs ($Z = 55$) is ^{133}Cs ($N = 78$), all of the Cs isotopes from ^{112}Cs, where $N = 57$ and $t_{1/2} = 0.5$ ms, to ^{148}Cs where $N = 93$ and $t_{1/2} = 0.15$ s, have been observed. At the low mass end of this series, the last

proton is unbound, and at the high mass end, the last neutron is less strongly bound than in lighter Cs isotopes.

The ground states of ^{112}Cs and ^{113}Cs decay by proton emission much or all of the time, and there are many cases where particles are emitted from excited states of the daughter following β^- or EC + β^+-decay. For example, ^{114}Cs decays by electron capture and/or β^+ emission to ^{114}Xe, and in 9% of these cases protons are emitted from excited states in ^{114}Xe that thereby populate levels in ^{113}I. In the other 91% of the decays, either the ground state is fed or γ-deexcitation from excited states leads to the ^{114}Xe ground state. At the other extreme, ^{147}Cs decays by β^--decay to ^{147}Ba, and in 43% of these cases neutrons are emitted from excited states in ^{147}Ba, thereby populating levels in ^{146}Ba. In the other 57% of the decays, either the ^{147}Ba ground state is fed directly or γ-deexcitation of excited states leads to the ^{147}Ba ground state.

A number of proton-rich nuclides are now known for which proton decay occurs from the ground state or from a low energy isomeric state (see the summary in Ref. 13). For some very light, highly neutron-rich nuclides, such as ^{7}He, ^{10}Li and ^{16}B, ground-state decay occurs by neutron emission alone.

4.6. α-Decay. In α-decay, the parent atom of atomic number Z and mass A emits an α-particle, a ^{4}He nucleus having $Z = 2$ and $A = 4$, and becomes an atom having atomic number $Z-2$ and mass $A-4$. From the conservation of energy, the observed energy of the α-particle will be

$$E(\alpha) = Q + E_P - E_D - E_R$$

where Q is the energy equivalent of the difference in mass of the parent atom and the sum of the masses of the daughter atom and a ^{4}He atom, E_P is the energy of the α-decaying parent nucleus level (not necessarily the ground state), E_D is the energy of the populated level in the daughter nucleus, and E_R is the recoil energy imparted to the atom. The recoil energy is

$$E_R = E(\alpha) \cdot M_\alpha/(M_P - M_\alpha)$$

where M_α and M_P are the masses of a ^{4}He atom and the parent atom, respectively. The parent often decays by α emission to several distinct levels in the daughter nucleus. The α-particle can carry off any number of units of angular momentum or spin, so this decay can occur to any daughter states (except between 0^+ and 0^- states). The probability for decay to each daughter level depends on the specific properties of the corresponding wave functions, but the strongest decays usually occur to levels having the same spin as the parent level.

In this decay process, only one particle is emitted and, because energy is conserved, there is a unique α-particle energy associated with decay to any given level in the daughter nucleus. This means that a measurement of the differences in the energies of the α-particles emitted in a radioactive decay give explicitly the differences in the energies of the levels in the daughter nucleus.

4.7. Spontaneous Fission. The spontaneous splitting of a heavy nucleus into two large fragments, usually accompanied by the release of a few neutrons, is termed spontaneous fission. A typical example is as follows:

$$^{252}_{98}\mathrm{Cf} \rightarrow ^{144}_{56}\mathrm{Ba} + ^{106}_{42}\mathrm{Mo} + 2\ ^{1}_{0}\mathrm{n}$$

This process occurs only for very heavy nuclei where the mass of the original nucleus is significantly larger than that of all the products. This excess mass appears as kinetic energy and in the excitation energy of the products. The large fragments emit γ-rays until the ground states are reached. The resulting fission-product nuclei are generally radioactive also. For example, in the subsequent β^--decay chains of $^{144}_{56}$Ba and $^{106}_{42}$Mo, the corresponding half-lives are ^{144}Ba (11.5 s) $\rightarrow$ ^{144}La (41 s) $\rightarrow$ ^{144}Ce (285 days) $\rightarrow$ ^{144m}Pr (7 min) $\rightarrow$ ^{144}Pr (17 min) $\rightarrow$ ^{144}Nd (2.3×10^{15} year) $\rightarrow$ ^{140}Ce (stable), and ^{106}Mo (8 s) $\rightarrow$ ^{106}Tc (36 s) $\rightarrow$ ^{106}Ru (374 days) $\rightarrow$ ^{106}Rh (30 s) $\rightarrow$ ^{106}Pd (stable). Spontaneous fission is observed for several U ($Z = 92$) and Pu ($Z = 94$) isotopes as well as for many of the more neutron-rich isotopes of elements having higher atomic number. Apart from U, all of these elements are synthetic.

4.8. Exotic Decays. In addition to the common modes of nuclear decay, two exotic modes have been observed. These decay modes are of theoretical interest because their long half-lives place strict constraints on the details of any theory used to calculate them.

Cluster Emission. Cluster emission is an exotic decay that has some commonalities with α-decay. In α-decay, two protons and two neutrons that are moving in separate orbits within the nucleus come together and leak out of the nucleus as a single particle. Cluster emission occurs when other groups of nucleons form a single particle and leak out. Several of the observed decays are shown in Table 10. The emitted clusters include ^{14}C, ^{20}O, ^{23}F, ^{22,24}Ne, ^{28,30}Mg, and ^{32,34}Si. The rare nature of these decays is indicated by the ratio of their probability to that of α-decay. These ratios, the inverse of the values in the second-last column of Table 10, are 10^{-9}–10^{-16}.

Double β-Decay. Double β-decay is the other class of exotic decay. The members of this class that are of interest are those in which the parent nuclide is stable against single β-decay because the corresponding decay energy is negative, or because the single β-decay is very highly hindered by spin-selection rules. Table 11 shows six selected cases where double β-decay has been observed; for several other nuclides, a significant lower limit has been established for the corresponding half-life. The decay energy indicates that for ^{48}Ca the single β-decay is possible, but it would be between states with $J^\pi = 0^+$ and $J^\pi = 6^+$ and this large spin change results in a very long half-life. In the other cases, single β-decay is forbidden by energy conservation.

The observation of double β-decay has been of particular interest because there are different concepts of how this decay can occur. The theoretical half-life depends on which concept is correct. Also, the predictions of the theory influence not only the design of the experiments used to observe the decay, but also the interpretation.

From the discussion on lepton conservation, it follows that the two emitted β's would be accompanied by two antineutrinos. This case is denoted $\beta\beta_2$. However, there is an alternative theoretical mechanism by which the two β's could be emitted without any neutrino, denoted $\beta\beta_0$. The experimental methods that are used to look for the double β-decay mode are often more sensitive to one of these decay modes than the other. The difference in the expected energy distribution of the electrons is clear from the fact that in the first case the total decay energy is divided between four particles, including the two antineutrinos that cannot be observed; in the second, it is only divided between the two electrons. As more exotic modes of decay are measured and more stringent lower limits are placed on some of the half-lives, the constraints on theory become even stronger.

5. Combined Nuclear and Atomic Processes

There are two processes where nuclear and atomic contributions are interrelated. These are the emission of electrons from the atomic shells as an alternative to the emission of a photon and the emission of bremsstrahlung photons in the β-decay process.

5.1. Internal Conversion. As an alternative to the emission of a γ-ray, the available energy of the excited nuclear state can be transferred to an atomic electron and this electron can then be ejected from the atom. The kinetic energy of this electron is $E_\gamma - E_B$ where E_B is the energy by which the electron was bound to the nucleus. Because the atomic electrons exist in a series of discrete levels, commonly denoted by K, L_1, L_2, L_3, M, etc (see Fig. 2), for each γ-ray there is a series of discrete internal-conversion lines that can be observed in an appropriate electron spectrometer.

The intensity of a conversion line can be expressed relative to that of the associated γ-ray as the internal-conversion coefficient (ICC), denoted as α. For example, α_K is the ratio of the number of electrons emitted from the K atomic shell to the number of photons emitted. For the other atomic levels, the corresponding conversion coefficients are denoted by α_{L1}, α_{L2}, α_M, etc. The total conversion coefficient is $\alpha = \Sigma_i \alpha_i$, where the sum includes all atomic shells or subshells. The conversion coefficients have strong dependences on the transition energy, multipolarity, atomic number, and electron shell, and values range over many orders of magnitude. Therefore, the measurement of internal-conversion coefficients can be a sensitive way to determine the multipolarity of the γ-ray.

A sample of theoretical conversion coefficients is given in Table 12, illustrating the great range of values. The most common case where two multipolarities compete is M1 + E2. For example, the α_K for M1 and E2 are nearly equal at $Z = 60$ and $E = 150$ keV. It is, however, relatively easy to determine the fraction of each of these components that is present if the relative intensity of the three L conversion lines can be measured. For the E2 component, the three intensities are almost equal ($\alpha_{L1} = 0.035$, $\alpha_{L2} = 0.050$, and $\alpha_{L3} = 0.048$), whereas for the M1 portion they vary by factors of 10 ($\alpha_{L1} = 0.050$, $\alpha_{L2} = 0.0037$, and $\alpha_{L3} = 0.00072$). The values for the mixed transition are just the weighted sum of these values. For example, for a 50% mixture of M1 and E2, the coefficients are $\alpha_{L1} = 0.042$, $\alpha_{L2} = 0.027$, and $\alpha_{L3} = 0.024$.

In addition to the possible multipolarities discussed in the previous sections, internal-conversion electrons can be produced by an E0 transition, in which no spin is carried off by the transition. Because the γ-rays must carry off at least one unit of angular momentum, or spin, there are no γ-rays associated with an E0 transition, and the corresponding internal-conversion coefficients are infinite. The most common E0 transitions are between levels with $J_i = J_f = 0$, where the other multipolarities cannot contribute. However, E0 transitions can also occur mixed with other multipolarities whenever $J_i^\pi = J_f^\pi$. For example, when $J_i = J_f = 2$ with $\Delta\pi = 0$, transitions of an $E0 + M1 + E2$ character are sometimes observed.

5.2. Internal Bremsstrahlung. Another type of radiation that originates in the atomic electron cloud as a direct consequence of a nuclear process is a continuous photon spectrum known as bremsstrahlung. This radiation is caused by the sudden change in the electric field on each electron around the atom resulting from the change in the nuclear charge associated with α, β^-, or electron-capture decay. This sudden change produces a continuous bremsstrahlung spectrum of photons that range in energy from 0 up to the decay energy. The probability of this process occurring is quite small, and only a small fraction of the decay energy is carried off by this radiation.

Table 13 gives calculated bremsstrahlung spectra for several radioisotopes. Because the decay energies of ^{54}Mn, ^{56}Cr, ^{177}Ta, and ^{177}Yb are all similar, a comparison of the spectra is meaningful. Electron capture gives a much lower intensity in the low energy bins than the β^--decay. The ^{54}V isotope has a much higher decay energy and, consequently, a higher bremsstrahlung yield.

6. Atomic Decays and Radiations

Of the modes of nuclear decay discussed above, two produce excitation of the atomic electron system. In electron capture an electron goes into the nucleus, leaving a hole in the electron shell. In internal conversion, energy is transferred to an electron, which is thereby ejected from the atom. The electron system promptly returns to its ground state by a series of processes that radiate away the excess energy. This energy can be evidenced in a series of electromagnetic photons, called X-rays, or by transfer of energy to additional electrons, which are then ejected. Here it is assumed that the atom is in an environment in which other electrons are available that can be attracted to this positively charged atom so that it becomes neutral and reaches its ground state. In a nonconducting medium or in empty space, the atom can in fact remain charged (see X-RAY TECHNOLOGY).

6.1. X-Rays. If an X-ray is emitted, it has an energy, ΔE, equal to the difference in the binding energies of the two atomic shells, $E_i - E_j$. If the original hole is in the K shell, the X-ray is called a K X-ray; if the hole is in the L shell it is an L X-ray. Because the hole can be filled by an electron from any of the several outer shells, X-ray spectra contain a large number of discrete lines.

The energies of the X-rays depend on the properties of the atom and not on those of the nucleus. Thus the energies of the X-rays do not give any information about the nuclear process that created the original hole. Also, because all K-shell

holes are equivalent, the relative emission probabilities for the various K X-rays are determined solely by the atomic properties. These do not give information about the related nuclear process. An exception is the case when only one nuclear transition produces all of the observed X-rays. In this case, the X-ray intensity enables the determination of the K-shell internal-conversion coefficient. Also, in some cases, careful measurements of the relative emission rates of the L X-rays can provide information about the related nuclear process. However, this is useful only if most of the L-shell holes are produced directly by internal conversion in the L subshells rather than by the filling of holes in the K shell.

When a hole in the ith shell is filled by an electron from the jth shell, the resulting hole in the latter shell that will, in turn, be filled by an electron from a higher kth shell. This may result in the emission of a second X-ray, such that one hole in an inner-electron shell can result in a cascade of several X-rays having ever-decreasing energies.

For holes in the ith shell, the fraction of the holes that result in X-rays when that hole is filled with an outer electron is called the fluorescent yield, ω_i, eg, ω_K and ω_{L_1}. The quantity ω_K has been computed theoretically, but the best values come from a simultaneous evaluation of the measured and theoretical values. The value of ω_K varies smoothly with the atomic number Z, and the fluorescence yields for each L subshell are smaller than the ω_K for the same Z. Table 14 gives selected values of the K- and L_1-shell binding energies, ω_K, ω_{L_2}, and relative emission probabilities of the K_α and K_β X-rays as a function of the atomic number, Z.

6.2. Auger Electrons. The fraction of the holes in an atomic shell that do not result in the emission of an X-ray produce Auger electrons. In this process, a hole in the ith shell is filled by an electron from the jth shell, and the available energy is transferred to a kth shell electron, which in turn is ejected from the atom with a kinetic energy $= E_i - E_j - E_k$. Usually, the most intense Auger electron lines are those from holes in the K shell and involve two L-subshell electrons. For example, assume an initial hole in the K shell is filled by an electron from the L_1 subshell and that the Auger process results in the ejection of an electron from the L_3 subshell. The kinetic energy of the latter electron is then equal to $E(K) - E(L_1) - E(L_3)$, and the electron is denoted as a KL_1L_3 Auger electron. The probability of producing a KXY Auger electron from a hole in the K shell is simply $(1 - \omega_K)$.

This process results in two holes in the L-electron shell, which then leads to two L X-rays, or two more Auger electrons, or one of each. In any case, there are more holes in the M or higher electron shells. Because the energies of the atomic electrons are discrete, the Auger electrons appear as discrete lines, although there may be very many lines which are, consequently, difficult to resolve. The energies of the Auger electrons and their intensities relative to the corresponding X-rays depend only on atomic parameters. Thus they do not give any information about the nuclear transitions that produced them beyond that already available from the X-ray spectrum.

7. Secondary Radiations

The previously discussed radiations have their origin in the atom in which the original decay took place. If the radiation reaching a detector is measured, there are other radiations that are observed.

7.1. External Bremsstrahlung. When a charged particle is decelerated or accelerated, it produces a continuous photon spectrum called external bremsstrahlung. When α-, β^--, or β^+-particles are emitted, they are scattered in the surrounding material and, in the process, they produce bremsstrahlung radiation. This spectrum is quite similar to the internal bremsstrahlung spectrum from β^-- or electron-capture decay. It is a continuum, ranging in energy from zero to the decay energy. Most of the photons have low energies. The number of photons produced per particle emitted depends on the atomic number of the material in which the particles are scattered and the Q-value of the decay.

7.2. Compton-Scattered Photons. When a γ-ray interacts in material, there are several processes that may occur. One of these is Compton scattering, in which part of the γ-ray energy is transferred to an atomic electron, and the part remaining is carried off by a secondary photon, as illustrated in Figure 6. The conservation of energy and momentum requires specific relations between the scattering angles for the photon and electron and their energies. Compton-scattered photons are generated in the surrounding material and observed in any γ-ray detector.

7.3. X-Rays and Annihilation Radiation. The interaction of γ-rays with matter produces the X-rays that are characteristic of the atoms in the material in which the interactions take place. Such X-rays appear in the measured spectra.

The β^+-particles that are emitted in the β^+-decay mode are slowed down in the material around the source. When these reach very low velocities they interact with an ordinary electron and the pair is annihilated. The corresponding energy of $2 \times m_0c^2$, or 1022 keV, is normally released in the form of two photons of 511 keV each, emitted in opposite directions.

In addition to Compton scattering, γ-rays having energies above 1022 keV interact with matter by a process called pair production, in which the photon is converted into a positron and an electron. The γ-ray energy in excess of the 1022 keV needed to create the pair is shared between the two new particles as kinetic energy. Each β^+-particle is then slowed down and annihilated by an electron producing two 511-keV photons.

7.4. Background Radiation. When the radiation from a radioactive source is measured, the spectrum also contains contributions from radiations originating from the detector environment. This includes radiations from the radioactivity in the materials of the detector itself, as well as from other experimental equipment and the structure of the building or nearby earth. There is also cosmic radiation that comes from space and interacts with the earth and atmosphere to produce radiations that may enter the detector, and thus be observed.

8. Decay Data

Most areas of research and applications involving the use of radioisotopes require a knowledge of what radiations come from each isotope. The particular application determines what type of information is needed. If the quantity of a radionuclide in a particular sample or at a particular location is to be determined and this value is to be determined from the γ-ray spectrum, the half-life of the nuclide and the energies and intensities or emission probabilities of the γ-rays of interest must be known. Usually it is preferable to use the γ-rays for an assay measurement because the α- and β-rays are much more readily absorbed by the source material, and may lose a considerable amount of their energy before reaching the sample surface. Once their characteristic energies have been altered, they can no longer be used to identify the parent radionuclide.

In research environments, where the configuration and activity level of a sample can be made to conform to the desires of the experimenter, it is now possible to measure the energies of many γ-rays to ± 0.01 keV and their emission rates to an uncertainty of $\sim 0.5\%$. As the measurement conditions deviate from the optimum, however, the uncertainty in the measured value increases. In most cases, where the counting rate is high enough to allow collection of sufficient counts in the spectrum, the γ-ray energies can nevertheless still be determined to $\sim \pm 0.5$ keV. If the configuration of the sample is not one for which the detector efficiency has been directly measured, however, the uncertainty in the γ-ray emission rate may increase to 5 or 10%.

For most applications, the decay parameters of the radionuclides of interest are known with sufficient accuracy for their uncertainties to be of no concern. Typically, this is the case if the uncertainty in the half-life is 0.1% or less and the uncertainty in the γ-emission probability is 1% or less.

There are single-volume resources available that contain the half-lives and γ-ray intensities for all radionuclides (24–26). More recent data can be obtained electronically from the Evaluated Nuclear Structure Data File (ENSDF) (Ref. 3 and subsequent updates) or the NuDat or MIRD databases derived from it (see Databases). Reference 12 also provides recently evaluated data for selected radioisotopes.

Table 15 shows data for several radionuclides, the γ-rays of which are often used to calibrate the efficiency of γ-ray detectors. For a number of these γ-rays the very high precision arises because the γ-ray occurs in essentially 100% of the decays of the nuclide, and only small corrections are needed to deduce the γ-emission probability. In other cases, the accuracy is high because a number of careful measurements have been performed. The γ-emission rate from a calibration source also depends on the activity of the source, and for these nuclides the uncertainty in the source activity is often the larger uncertainty.

The half-lives, γ-ray energies, and γ-ray emission probabilities given in Table 15 are the data needed if the amount of a radioisotope present in a sample is to be measured. However, for some applications of radionuclides, additional data concerning the decay are needed. For example, if a radionuclide is to be injected or implanted *in vivo*, it is necessary to have data on all of the radiations produced in order to assess the total impact on the cell structure. Table 16 gives

samples of the data that can be useful in this latter case. Such information can be obtained from some of the references above. There also exist computer codes that can use the decay data from the ENSDF database to produce this type of information for any radionuclide, eg, RADLIST (29).

9. Applications

9.1. Dating. Naturally occurring radioisotopes are used in archaeology and paleontology to determine the age of, for example, a tree that lived a few thousand years ago or a rock that was formed a few million years ago. The idea of using the radiation from an object to determine its age goes back to the early years after the discovery of radioactivity. In $\sim$ 1905, the ages of certain ores were estimated from their radioactivity. Although these estimates were too low by a large factor, they were good enough to challenge the concept that the earth had been created only a few thousand years ago.

There are two methods of using radioactive decays to determine the age of an object. One method, applicable to formerly living organisms, is based on the assumption that the specific activity, ie, the number of disintegrations per second per gram, is known for the time at which the organism was alive. The time since death is then determined by comparing this with the measured specific activity. The other method, applicable to nonliving objects, determines age from the amounts of both the radioactive parent and the usually stable daughter isotope present in a sample. In this latter case, all of the daughter atoms must be assumed to have come from the parent, or else an independent method of determining what fraction of the daughter atoms came from the decay of the parent must be available. Table 17 lists half-lives of several radioisotopes that have been used for dating.

The use of ^{14}C to determine the lapse of time since a living plant or animal died was developed early on. The ^{14}C isotope produced in the atmosphere by the $^{14}N + n \rightarrow {}^{14}C + p$ reaction, becomes distributed in the air and ground along with the stable isotopes of carbon, ^{12}C (98.89%) and ^{13}C (1.11%). The ^{14}C is then taken up by living bodies in food along with the stable isotopes of carbon. When the organism dies, however, it ceases taking up ^{14}C, so the amount present decreases with the characteristic half-life of ^{14}C. In the dating of old trees, it can be assumed that the specific activity of ^{14}C is the same today in living trees, or at least in specific types of trees, as it was a few thousand years ago. Because ^{14}C decays purely by β-decay, which has a decay energy of only 155 keV, care must be taken in the measurement of the activity. The material must be processed to extract the carbon and prepare a thin solid or gaseous sample that allows the β-particles to reach the detector. The time since the sample was last in equilibrium with the ^{14}C in the atmosphere is simply the time it has taken for its specific activity to decrease from the value for currently living trees of the same type to the measured value. The range of time where this method is most useful is around one half-life, ie, $\sim$ 6000 years, but much older objects have been successfully dated by this means.

Since this method was perfected, several other dating methods that do not involve radioactivity have been developed. The one used to date trees is the

counting of the annual growth rings. When comparing results from ^{14}C dating and ring counting, some discrepancies were identified. From these differences it was concluded that the rate of ^{14}C production in the atmosphere was not the same in the past as in the late twentieth century, but the ring counting data have been used to determine the historical atmospheric concentrations of ^{14}C. Although this knowledge has made the use of ^{14}C dating more complex, requiring corrections to the simple calculated values, the method is nevertheless a very useful one.

The other radioisotopes in Table 17 have much longer half-lives and can be used to determine the ages of materials that are of the order of a million years old. Consequently, these are especially useful for dating rocks. In these cases, the amount of the parent present can be determined either by measuring its radiation or by counting the number of atoms. The daughters are stable, so their abundance must be ascertained by counting the atoms, or by some chemical assay method. In all of these cases there is more than one element of the same mass, so a simple mass spectrometer measurement cannot be employed until the daughter atoms have been chemically purified (see MASS SPECTROMETRY).

In these cases, what is usually measured is not the time of the original formation of the rocks, but the time at which the parent and daughter elements were last separated. That is, if the rocks were remelted at some point in their history in a manner that removed the daughter elements, this would be the age measured. For the ^{40}K measurements this is especially important. The daughter is a gas and thus could escape at any time when it was not sealed in. The decay sequences of ^{232}Th, ^{235}U, and ^{238}U all have gaseous members in their decay chains (see Tables 1 and 2), but the final members are solids. Consequently, in these cases, it is only necessary that the gaseous members be retained for periods of several of their half-lives for the measured ages to be unaffected by loss of the gases. In the ^{238}U chain, the ^{222}Rn has a half-life of 3.8 days, so diffusion out of the region of the ^{238}U may occur, but in the ^{232}Th chain the ^{220}Rn has a half-life of only 55 s, so diffusion would be less likely in that case.

All of these daughter isotopes occur naturally; thus it is always necessary to show that in the rocks of interest the daughter element present originated only from the decay of the parent; otherwise, the fraction of the daughter isotope that is from the decay of the parent must be separately determined. For example, the presence of ^{87}Sr in the absence of the naturally more abundant ^{88}Sr (82.58%) would clearly indicate that its origin is from the decay of ^{87}Rb. For the Pb isotopes, a more detailed set of measurements might be needed. In this case, the normal Pb abundances can be altered by the presence of any or all of the indicated Th and U isotopes, so not only the abundances of the Pb isotopes, but also those of the potential parent isotopes must be determined.

9.2. Medical Diagnoses and Treatments. Radioisotopes have become very important in the practice of modern medicine, for both diagnosis and treatment. Some diagnoses are done by injecting a radionuclide in a biochemical form such that it goes to a particular organ, and the measured radiation then allows the functional level of that organ to be determined. A common treatment is to expose a portion of the body, eg, a tumor, to radiation from a radioisotope with the source either internal or external to the body. Another usage involves radioactively labeled antibodies (see IMMUNOASSAY).

There are many radioisotopes that are used for medical diagnosis (see Radioactive Elements; Radiopharmaceuticals). One example is the monitoring of blood flow to various regions of the heart using ^{201}Tl, which has a half-life of 3.0 days. One procedure involves having the patient walk on a treadmill at a pace that forces the body and the heart to work quite hard. Then the thallium compound is injected into the blood stream and is attracted to the active heart muscle. Using a multidetector γ-ray measurement system that can be rotated around the reclining patient, the approximate origin of the γ-rays from within the heart is measured. A computer analysis of these data produces computer assisted tomography (CAT) scan pictures that can be displayed to show the distribution of the radioactivity in different regions of the heart. If a coronary artery is blocked, the radioactive blood does not reach the corresponding part of the heart as quickly as it reaches other portions. Although the spatial resolution of the measurement and analysis system is not fine enough to give detailed information about blockages along each artery, it does identify the portions of the heart that are not receiving normal blood flow. The decay data for ^{201}Tl (see Table 16) can be used in the calculation of the radiation dose received by the various organs of the patient. Because ^{201}Tl decays by electron capture, a large fraction of the decay energy of 482 keV is emitted in the form of neutrinos, which do not contribute to the patient's radiation dose.

The radioisotopes ^{99m}Tc and ^{131}I (see Table 16) are often used for medical purposes. The ^{99m}Tc isotope has a half-life of only 6 h, which would normally make it difficult to transport it from a production facility to the medical facility. However, one can supply the longer lived 2.7-day ^{99}Mo in a chemical form that allows one to separate out, generate or milk, the daughter ^{99m}Tc when the latter is needed.

Another medical use of radioisotopes, such as ^{60}Co, is to irradiate certain tissues within the body. An intense source of ^{60}Co in a heavily shielded facility provides a highly collimated beam of γ-rays that impinge on a tumor in order to kill its cells.

9.3. Other Applications. Radioactive isotopes have found application in many fields of scientific research besides nuclear physics and the applications to medicine and the dating of objects discussed above.

Just as radioisotopes can be inserted into molecules and tracked by detecting emitted radiation as they proceed through a biological process, chemical, and physical processes can be studied by the addition of radioisotopes as tracers in forms that mimic the regular constituents of the process. Measurements of the radiation levels can lead to determination of the distribution of the chemical in the process. Radioisotopes have been injected into underground water systems in order to determine the flow patterns and rates in geological formations. They have also been used in measurements of water run-off from rain and snow, or flow rates in rivers.

There are numerous industrial applications for radioisotopes. A simple example is the determination of the thickness of some item that is being formed, or of the density of a flow stream in a chemical process, by measuring the attenuation of β- or γ-radiation as it passes through the material. Another version of this type of density measurement is the search for cracks or thin spots in

welds by measuring the variation in the intensity of the radiation passing through an object.

A novel application for radioisotopes is their use for the nondestructive analysis fine arts objects (see FINE ART EXAMINATION AND CONSERVATION; NONDESTRUCTIVE EVALUATION).

Radioisotopes impact our everyday lives. Most household smoke detectors contain a small amount of americium. Uranium and plutonium radioisotopes constitute the fuel for nuclear reactors (qv); those reactors are employed by many commercial power companies to produce electricity or by radiopharmaceutical companies to generate a wide range of radionuclides currently used in medical therapy and diagnosis. Strong radiation sources are used in food preservation, eg, to kill parasites or prevent sprouting of root vegetables after harvest, and they can effectively sterilize medical equipment such as syringes.

Uranium and plutonium radioisotopes have also found application, of course, as the critical components in nuclear weapons.

It is worth noting that, for the sake of brevity, only a sample of the many and varied uses of radioisotopes has been mentioned here.

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Table 1. **Naturally Occurring Radioisotopes in the ^{238}U Chain**

Parent[a]	Original name	Half-life[b]	Decay mode[c]	Branching,[b]%	Daughter
^{238}U		$4.468\ (3) \times 10^{9}$ year	α	100	
^{234}Th	U X1	24.10 (3) days	β^-	100	
^{234m}Pa	U X2	1.17 (3) min	IT	0.16 (4)	^{234}Pa
			β^-	99.84 (4)	^{234}U
^{234}Pa		6.70 (5) h	β^-	100	
^{234}U	U II	$2.455\ (6) \times 10^{5}$ year	α	100	
^{230}Th	ionium	$7.54\ (3) \times 10^{4}$ year	α	100	
^{226}Ra	radium	1600 (7) year	α	100	
^{222}Rn	Ra emanation	3.8235 (3) days	α	100	
^{218}Po	RaA	3.10 (2) min	α	99.980 (2)	^{214}Pb
			β^-	0.020 (2)	^{218}At
^{218}At		1.5 (3) s	α	99.9	^{214}Bi
			β^-	0.1	^{218}Rn
^{218}Rn		35 (5) ms	α	100	^{214}Po
^{214}Pb	RaB	26.8 (9) min	β^-	100	^{214}Bi
^{214}Bi	RaC	19.9 (4) min	β^-	99.979 (1)	^{214}Po
			α	0.021 (1)	^{210}Tl
^{214}Po	RaC′	164.3 (20) μs	α	100	^{210}Pb
^{210}Tl	RaC″	1.30 (3) min	β^-	100	^{210}Pb
^{210}Pb	RaD	22.20 (22) year	β^-	99.9999983 (4)	^{210}Bi
			α	0.0000017 (4)	^{206}Hg
^{210}Bi	RaE	5.012 (5) days	β^-	99.99987 (1)	^{210}Po
			α	0.00013 (1)	^{206}Tl
^{210}Po	RaF	138.376 (2) days	α	100	^{206}Pb
^{206}Hg		8.15 (10) min	β^-	100	^{206}Tl
^{206}Tl		4.200 (17) min	β^-	100	
^{206}Pb	RaG	[d]			

[a] Each radioisotope decays to the next entry in the table, unless otherwise noted in the last column.
[b] Ref. 3. The uncertainty in the last digit or digits is shown in parentheses.
[c] IT = internal transition.
[d] Stable.

Table 2. **Naturally Occurring Radioisotopes in the ^{232}Th Chain**

Parent[a]	Original name	Half-life[b]	Decay mode	Branching,[b] %	Daughter
^{232}Th		1.405 (6) × 10^{10} year	α	100	
^{228}Ra	mesothorium I	5.75 (3) year	β^-	100	
^{228}Ac	mesothorium II	6.15 (2) h	β^-	100	
^{228}Th	radiothorium	1.9116 (16) year	β^-	100	
^{224}Ra	thorium X	3.66 (4) days	α	100	
^{220}Rn	thoron	55.6 (1) s	α	100	
^{216}Po	ThA	0.145 (2) s	α	100	
^{212}Pb	ThB	10.64 (1) h	β^-	100	
^{212}Bi	ThC	60.55 (6) min	β^-	64.06 (6)	^{212}Po
			α	35.94 (6)	^{208}Tl
^{212}Po	ThC′	0.299 (2) μs	α	100	
^{208}Tl	ThC″	3.053 (4) min	β^-	100	
^{208}Pb	ThD	[c]			

[a] Each radioisotope decays to the next entry in the table, unless otherwise noted in the last column.
[b] Ref. 3. The uncertainty in the least significant digit(s) is shown in parentheses.
[c] Stable.

Table 3. **Naturally Occurring Radioisotopes[a]**

Radioisotope	Abundance,[b,c] %	Half-life,[c,d] year	Decay mode[e]	Q-value,[f] keV	Stable daughter
^{40}K	0.0117 (1)	1.248 (3) × 10^9	β^-	1311.07	^{40}Ca
			ε	1504.69	^{40}Ar
^{87}Rb	27.83 (2)	4.81 (9) × 10^{10}	β^-	272.6	^{87}Sr
^{113}Cd	12.22 (12)	7.7 (3) × 10^{15}	β^-	320	^{113}In
^{115}In	95.71 (5)	4.41 (25) × 10^{14}	β^-	499	^{115}Sn
^{123}Te	0.89 (3)	>9.2 × 10^{16}	ε	52.2	^{123}Sb
^{138}La	0.090 (1)	1.02 (1) × 10^{11}	β^-	1044	^{138}Ce
			ε	1737	^{138}Ba
^{144}Nd	23.8 (3)	2.29 (16) × 10^{15}	α	1905.2	^{140}Ce
^{147}Sm	14.99 (18)	1.06 (2) × 10^{11}	α	2310.5	^{143}Nd
^{148}Sm	11.24 (10)	7 (3) × 10^{15}	α	1986.1	^{144}Nd
^{152}Gd	0.20 (1)	1.08 (8) × 10^{14}	α	2203.0	^{148}Sm
^{174}Hf	0.16 (1)	2.0 (4) × 10^{15}	α	2497.4	^{170}Yb
^{176}Lu	2.59 (2)	4.00 (22) × 10^{10}	β^-	1190.2	^{176}Hf
^{180m}Ta	0.012 (2)	>1.2 × 10^{15}	β^-	708	^{180}W
			ε	852.2	^{180}Hf
^{186}Os	1.59 (3)	2.0 (11) × 10^{15}	α	2823.1	^{182}W
^{187}Re	62.60 (2)	4.35 (13) × 10^{10}	β^-	2.469	^{187}Os
^{190}Pt	0.014 (1)	6.5 (3) × 10^{11}	α	3251	^{186}Os

[a] Excluding radon, radium, actinides, and transactinides.
[b] From Ref. 4.
[c] The uncertainty in the least significant digit(s) is shown in parentheses.
[d] From Ref. 5.
[e] ε = electron capture.
[f] Q-value = decay energy; data are from Ref. 6.

Table 4. **Properties of Stable Particles Associated With Radioactive Decay**

Name	Symbol	Energy, MeV	Charge	Spin
proton	p	938	+1	½
neutron[a]	n	940	0	½
electron	e^- or β^-	0.511	−1	½
positron	e^+ or β^+	0.511	+1	½
electron neutrino	ν	~0.0	0	½
electron antineutrino	$\bar{\nu}$	~0.0	0	½
photon	γ or x	0.0	0	1

[a] A free neutron has a half-life of 10.4 min, but a neutron is stable when bound in a nucleus.

Table 5. **Classification of β-Decays**[a]

Classification	ΔJ[b]	$\Delta\pi$[c]	Relative emission probability[a]
allowed	0, 1	no	$\equiv 10^{+2}$ (0^+ states excluded)
1st forbidden	0, 1	yes	$10^{+0.8}$
unique 1st forbidden	2	yes	$10^{-1.4}$
2nd forbidden	2	no	$10^{-4.4}$
unique 2nd forbidden	3	no	$10^{-7.4}$
3rd forbidden	3	yes	$10^{-9.4}$
unique 3rd forbidden	4	yes	$10^{-13.0}$
4th forbidden	4	no	$10^{-15.3}$

[a] Values are based on the centroids of experimental data summarized in Ref. 9 for the relevant transition classifications. Note, however, that the distribution of values for each classification has a significant width. Also, the allowed transitions to or from a 0^+ state constitute three separate subcategories whose emission probabilities differ markedly from those for all other allowed transitions.
[b] The parameter ΔJ is the difference between the spins of the parent and daughter states.
[c] The parameter $\Delta\pi$ is the change in parity. Parity is either + or −; change in parity either does or does not occur.

Table 6. **Ratios for *K* and *L* Capture, and for β^+ Emission and Electron Capture**[a]

Decay energy, keV	Classification	*K*/*L* capture	Capture/β^+
500	allowed and 1st forbidden	6.21	no β^+
	unique 1st forbidden	4.95	no β^+
	unique 2nd forbidden	3.63	no β^+
1500	allowed and 1st forbidden	6.89	285.5
	unique 1st forbidden	6.51	1904
	unique 2nd forbidden	6.08	9812
2000	allowed and 1st forbidden	6.98	19.92
	unique 1st forbidden	6.70	87.5
	unique 2nd forbidden	6.38	294.0
3500	allowed and 1st forbidden	7.09	0.98
	unique 1st forbidden	6.94	2.78
	unique 2nd forbidden	6.77	6.23
5000	allowed and 1st forbidden	7.14	0.24
	unique 1st forbidden	7.03	0.58
	unique 2nd forbidden	6.91	1.14

[a] Values are for decay to a $Z = 60$ daughter nuclide; they were obtained from the computer code LOGFT that calculates values from relations in Ref. 10.

Table 7. **Calculated Partial Half-Lives for γ-Ray Transitions**[a,b]

Multipolarity	Half-life, s			
	$E_\gamma = 10$ keV	$E_\gamma = 100$ keV	$E_\gamma = 1000$ keV	$E_\gamma = 10{,}000$ keV
E1	3.1×10^{-10}	3.1×10^{-13}	3.1×10^{-16}	3.1×10^{-19}
E2	2.1×10^{-1}	2.1×10^{-6}	2.1×10^{-11}	2.1×10^{-16}
E3	$2.0 \times 10^{+8}$	$2.0 \times 10^{+1}$	2.0×10^{-6}	2.0×10^{-13}
E4	$3.0 \times 10^{+17}$	$3.0 \times 10^{+8}$	3.0×10^{-1}	3.0×10^{-10}
M1	2.2×10^{-8}	2.2×10^{-11}	2.2×10^{-14}	2.2×10^{-17}
M2	$1.4 \times 10^{+1}$	1.4×10^{-4}	1.4×10^{-9}	1.4×10^{-14}
M3	$1.4 \times 10^{+10}$	$1.4 \times 10^{+3}$	1.4×10^{-4}	1.4×10^{-11}
M4	$2.1 \times 10^{+19}$	$2.1 \times 10^{+10}$	$2.1 \times 10^{+1}$	2.1×10^{-8}

[a] Ref. 1.
[b] Weisskopf single-particle estimates for mass 100 and four selected transition energies.

Table 8. **Internal-Pair Formation Coefficients**[a,b]

E_γ, keV	Coefficient			
	$E1, Z = 20$	$E1, Z = 50$	$M1, Z = 20$	$M1, Z = 50$
1100	0.0000112	0.0000037	0.00000064	0.00000041
1400	0.000190	0.000156	0.0000392	0.0000438
1800	0.000496	0.000458	0.000168	0.000195
2600	0.00102	0.000992	0.000504	0.000580
4000	0.00168	0.00166	0.00104	0.00117
8000	0.00271	0.00275	0.00199	0.00224

[a] Ref. 11.
[b] The ratio of the number of $e^- + \beta^+$ pairs to the number of γ-rays emitted.

Table 9. **γ-Ray Energies (E_γ) and Emission Probabilities (P_γ) for ^{24}Na and ^{60}Co**[a]

Parent nuclide	E_γ, keV	P_γ,[b] %	Multipolarity	ICC[c] $\times 10^3$	IPFC[b,d,e] $\times 10^3$	Total transition probability,[b] %
^{24}Na	996.09	0.00123 (27)	M1 + 18.1 % E2	0.017	0.0	0.00123 (27)
	1368.626	99.9935 (5)	E2	0.0104	0.045	99.9990 (3)
	2754.007	99.872 (8)	E2	0.0028	0.68	99.940 (7)
	2869.50	0.00024 (3)	M1 + 99.8 % E2	0.0026		0.00024 (3)
	3866.14	0.056 (7)	E2	0.0015		0.056 (7)
	4237.96	0.00084 (10)	E2	0.0016		0.00084 (10)
^{60}Co	347.14	0.0075 (4)	[E2]	5.54	0.0	0.0075 (4)
	826.10	0.0076 (8)	M1 + 45 % E2	0.33	0.0	0.0076 (8)
	1173.228	99.85 (3)	E2(+M3)	0.168	0.0062	99.87 (3)
	1332.492	99.9826 (6)	E2	0.128	0.034	99.9988 (2)
	2158.57	0.0012 (2)	E2	0.0491		0.0012 (2)
	2505.692	0.0000020 (4)	E4	0.086		0.0000020 (4)

[a] Data are from Ref. 12 (^{24}Na) and Ref. 3 (^{60}Co).
[b] Uncertainty in last digit or digits is shown in parentheses.
[c] Internal conversion coefficient = ICC.
[d] Internal pair formation coefficient = IPFC.
[e] Values not given are small compared to the uncertainty in P_γ.

Table 10. **Exotic Radioactive Decays with Emission of Clusters**[a]

Parent	Cluster	Daughter	Partial half-life, year			
			Cluster decay[a]	α Decay[b]	$t_{1/2\ \text{cluster}}/t_{1/2\ \alpha}$	SF decay[b]
^{221}Fr	^{14}C	^{207}Tl	1.1×10^{7}[c]	9.3×10^{-6}	1.2×10^{12}	
^{221}Ra	^{14}C	^{207}Pb	7.7×10^{5}[c]	8.9×10^{-7}	8.7×10^{11}	
^{222}Ra	^{14}C	^{208}Pb	3.2×10^{3}	1.2×10^{-6}	2.7×10^{9}	
^{223}Ra	^{14}C	^{209}Pb	3.5×10^{7}[d]	3.1×10^{-2}	1.1×10^{9}	
^{224}Ra	^{14}C	^{210}Pb	2.6×10^{8}	1.0×10^{-2}	2.6×10^{10}	
^{225}Ac	^{14}C	^{211}Bi	6.0×10^{9}[e]	2.7×10^{-2}	2.2×10^{11}	
^{226}Ra	^{14}C	^{212}Pb	7.0×10^{13}	1.6×10^{3}	4.4×10^{10}	
^{228}Th	^{20}O	^{208}Pb	1.7×10^{13}	1.9×10^{0}	8.9×10^{12}	
^{230}Th	^{24}Ne	^{206}Hg	1.3×10^{17}	7.5×10^{4}	1.7×10^{12}	
^{230}U	^{22}Ne	^{208}Pb	1.2×10^{12}[f]	5.7×10^{-2}	2.1×10^{13}	
^{231}Pa	^{23}F	^{208}Pb	3.3×10^{18}[g]	3.3×10^{4}	1.0×10^{14}	
^{231}Pa	^{24}Ne	^{207}Tl	2.4×10^{15}[g]	3.3×10^{4}	7.3×10^{10}	
^{232}U	^{24}Ne	^{208}Pb	7.9×10^{12}	6.9×10^{1}	1.1×10^{11}	8×10^{13}
^{233}U	^{24}Ne/^{25}Ne	^{209}Pb/^{208}Pb	2.2×10^{17}	1.6×10^{5}	1.4×10^{12}	1.2×10^{17}
^{234}U	^{28}Mg	^{206}Hg	1.7×10^{18}	2.5×10^{5}	6.8×10^{12}	1.4×10^{16}
^{234}U	^{24}Ne/^{26}Ne	^{210}Pb/^{208}Pb	2.7×10^{18}	2.5×10^{5}	1.1×10^{13}	1.4×10^{16}
^{235}U	^{24}Ne/^{25}Ne	^{211}Pb/^{210}Pb	8.4×10^{19}	7.0×10^{8}	1.2×10^{11}	1.0×10^{19}
^{236}U	^{30}Mg	^{206}Hg	$\sim 1.2 \times 10^{20}$[h]	2.3×10^{7}	$\sim 5.2 \times 10^{12}$	2.4×10^{16}
^{236}Pu	^{28}Mg	^{208}Pb	1.5×10^{14}	2.9×10^{0}	5.2×10^{13}	3.5×10^{9}
^{238}Pu	^{32}Si	^{206}Hg	6.0×10^{17}	8.8×10^{1}	6.8×10^{15}	4.6×10^{10}
^{238}Pu	^{28}Mg/^{30}Mg	^{210}Pb/^{208}Pb	1.6×10^{18}	8.8×10^{1}	5.3×10^{16}	4.6×10^{10}
^{242}Cm	^{34}Si	^{208}Pb	4.4×10^{15}[i]	4.5×10^{-1}	9.8×10^{15}	7.0×10^{6}

[a] From summary of experimental data given in Ref. 14, unless otherwise specified.
[b] From Ref. 3.
[c] From Ref. 15.
[d] Ref. 16.
[e] Recommended value from Ref. 17.
[f] Ref. 18.
[g] Ref. 19.
[h] Ref. 20.
[i] Ref. 21.

Table 11. **Selected Experimental Half-Life Results for Double β Decay**[a]

Parent	Daughter	β-decay energy,[a] keV	ββ-decay energy,[a] keV	Mode[b]	Half-life,[c] year	ν mass, eV[c]
^{48}Ca	^{48}Ti	+282	4274	$\beta\beta_0$	$>9.5\times10^{21}$[d]	<8.3
				$\beta\beta_2$	4.2×10^{19}	
^{76}Ge	^{76}Se	−923.5	2039	$\beta\beta_0$	$>1.9\times10^{25}$	<0.35
				$\beta\beta_2$	1.3×10^{21}	
^{82}Se	^{82}Kr	−97.5	2995.5	$\beta\beta_0$	$>2.7\times10^{22}$[e]	<5
				$\beta\beta_2$	9.2×10^{19}	
^{100}Mo		−168	3035	$\beta\beta_0$	$>5.5\times10^{22}$	<2.1
				$\beta\beta_2$	8.0×10^{18}	
^{130}Te	^{130}Xe	−419	2530.3	$\beta\beta_0$	$>2.1\times10^{23}$	<2
				$\beta\beta_2$	2.7×10^{21}	
^{150}Nd	^{150}Pr	−86	3367.7	$\beta\beta_0$	$>1.2\times10^{21}$	<3
				$\beta\beta_2$	7×10^{18}	

[a] Ref. 6.
[b] The symbol $\beta\beta_2$ signifies the emission of 2 βs and 2 neutrinos and $\beta\beta_0$ signifies the emission of 2 βs and no neutrinos.
[c] From Ref. 22, unless otherwise indicated; values given as limits are quoted at 90% confidence level, unless noted to the contrary.
[d] Limit given at 76% confidence level.
[e] Limit given at 68% confidence level.

Table 12. **Calculated Internal-Conversion Coefficients for γ Rays**[a,b]

E_γ, keV	Multi-polarity	α_K	α_{L1}	α_{L2}	α_{L3}	α
			Values for $Z = 30$			
20	E1	6.02	0.485	0.0696	0.125	6.80
	E2	150.1	11.8	22.6	39.1	234.2
	E3		184.6	3415	5769	13,600
	M1	5.41	0.539	0.0344	0.0132	6.09
	M2	241.2	34.8	3.39	9.19	296.2
	M3	6279	1629	238.2	2060	10840
150	E1	0.0158	0.00149	0.0000386	0.000065	0.0176
	E2	0.126	0.0117	0.00110	0.00147	0.143
	E3	0.844	0.0766	0.0222	0.0262	0.988
	M1	0.0189	0.00188	0.0000592	0.000026	0.0212
	M2	0.139	0.0146	0.000898	0.000613	0.158
	M3	0.969	0.1084	0.01085	0.0142	1.123
1000	E1	0.000115	0.0000112	0	0	0.000128
	E2	0.000265	0.0000260	0	0	0.000296
	E3	0.000553	0.0000543	0	0	0.000619
	M1	0.000227	0.0000223	0	0	0.000253
	M2	0.000516	0.0000512	0	0	0.000576
	M3	0.001076	0.0001078	0	0	0.001205
			Values for $Z = 60$			
20	E1		1.056	0.759	1.178	3.802
	E2		4.65	774	1105	2419
	E3		1529	111289	156157	3.645E5
	M1		17.73	1.583	0.325	25.0
	M2		1921	125.8	1033	4018
	M3		7.78E4	5509	4.22E5	6.84E5
150	E1	0.0730	0.00781	0.00105	0.00130	0.0859
	E2	0.356	0.0351	0.0501	0.0476	0.527
	E3	1.470	0.1393	1.064	0.872	4.163
	M1	0.392	0.0501	0.00367	0.000717	0.461
	M2	2.55	0.421	0.0494	0.0510	3.22
	M3	13.1	2.95	0.519	1.514	19.55
1000	E1	0.000810	0.000096	0	0	0.000940
	E2	0.00192	0.000231	0.0000219	0.0000120	0.00225
	E3	0.00400	0.000499	0.000105	0.0000339	0.00481
	M1	0.00299	0.000372	0.000015	0	0.00348
	M2	0.00732	0.000949	0.0000592	0.0000118	0.00861
	M3	0.01484	0.00202	0.000181	0.0000594	0.0177
			Values for $Z = 90$			
20	E1			*	3.06	5.24
	E2			*	1.059E4	1.819E4
	E3			*	1.132E6	2.58E6
	M1			*	2.19	116.8
	M2			*	2.67E4	5.54E4
	M3			*	1.61E7	2.48E7
150	E1	0.147	0.0180	0.00740	0.00596	0.189
	E2	0.241	0.0701	0.781	0.463	2.042
	E3	0.376	0.936	15.09	7.24	33.0
	M1	5.06	0.858	0.0915	0.00491	6.33
	M2	21.25	6.77	0.853	1.224	33.3
	M3	43.3	40.4	6.85	40.1	167.0

1000	E1	0.00288	0.000408	0.0000438	0.0000226	0.00351
	E2	0.00775	0.00124	0.000467	0.0000958	0.01016
	E3	0.0170	0.00321	0.00234	0.000292	0.0248
	M1	0.0294	0.00483	0.000440	0.0000227	0.0364
	M2	0.0651	0.0119	0.00156	0.000163	0.0832
	M3	0.1135	0.0233	0.00425	0.00113	0.1520

[a] From a computer file based on calculations published in Ref. 23.
[b] A zero indicates the value is >0 but <0.00001, a blank indicates that the value is 0 because the γ-ray energy is too low to eject the corresponding electrons, and an * means that the γ-ray energy is just above the binding energy so conversion occurs, but is too low to allow application of the theoretical tables.

Table 13. **Calculated Internal-Bremsstrahlung Spectra**[a]

Decay mode	Energy, keV	Average IB[b] energy, keV	Energy bin,[c] keV	Average energy in bin,[c] keV	Photon intensity, %
			^{54}Mn		
EC	1377	0.038	10–20	0.000052	0.00037
			20–40	0.000131	0.00044
			40–100	0.00151	0.0021
			100–300	0.021	0.0103
			300–542	0.0149	0.0041
			^{56}Cr		
β^-	1617	0.90	10–20	0.025	0.17
			20–40	0.048	0.166
			40–100	0.129	0.20
			100–300	0.31	0.18
			300–600	0.25	0.060
			600–1300	0.116	0.0156
			1300–1508	0.00026	0.000020
			^{54}V		
β^-	7042	3.5	10–20	0.044	0.31
			20–40	0.087	0.30
			40–100	0.25	0.38
			100–300	0.72	0.40
			300–600	0.81	0.19
			600–1300	1.08	0.126
			1300–2500	0.44	0.027
			2500–3387	0.0054	0.00021
			^{177}Ta		
EC	1158	0.53	10–20	0.00029	0.0023
			20–40	0.0035	0.0102
			40–100	0.28	0.50
			100–300	0.040	0.021
			300–600	0.112	0.025
			600–1158	0.098	0.0133
			^{177}Yb		
β^-	1398	0.56	10–20	0.018	0.126
			20–40	0.034	0.120
			40–100	0.091	0.141
			100–300	0.21	0.119
			300–600	0.143	0.035
			600–1300	0.050	0.0067
			1300–1398	0.0000053	0.00000040

[a] Data are from Ref. 24.
[b] Internal bremsstrahlung = IB.
[c] The bin is the range of energy over which the portion of the spectrum is summed or integrated.

Table 14. **Selected Values of the K and L_1 Electron-Binding Energies, K- and L_2-Shell Fluorescent Yields, and K_α/K_β X-Ray Intensity Ratio**[a]

Atomic number, Z	Binding energy, keV		Fluorescent yield		X-ray intensity ratio, K_α/K_β
	K	L_1	ω_K	ω_{L_2}	
1	0.013				
10	0.8701	0.0485	0.018		
20	4.0381	0.4378	0.163	0.00033	9.6
30	9.6586	1.1936	0.474	0.011	8.2
40	17.9976	2.5316	0.730	0.028	5.9
50	29.2001	4.4647	0.862	0.065	4.9
60	43.5689	7.1260	0.921	0.124	4.4
70	61.3323	10.4864	0.951	0.222	4.0
80	83.1023	14.8393	0.965	0.347	3.6
90	109.6500	20.4720	0.971	0.479	3.5
100	141.9260	27.5740	0.976	0.506	3.4

[a] Values are from Appendix C of Ref. 24.

Table 15. **Selected Decay Data for Radionuclides Useful for the Energy and Efficiency Calibration of γ-Ray Detectors**[a]

Radionuclide	$T_{1/2}$[a,b,c]	E_γ[c,d] keV	P_γ[c,e] %
^{22}Na	2.6027 (10) year	1274.537 (7)	99.935 (15)
^{24}Na	14.951 (3) h	1368.626 (5)	99.9936 (15)
		2754.007 (11)	99.855 (5)
^{46}Sc	83.79 (4) days	889.271 (2)	99.9844 (16)
		1120.537 (3)	99.9874 (11)
^{51}Cr	27.7025 (24) days	320.0824 (4)	9.86 (5)
^{54}Mn	312.12 (6) days	834.838 (5)	99.9758 (24)
^{57}Co	271.74 (6) days	14.4129 (6)[f]	9.16 (15)
		122.06065 (12)	85.60 (17)
		136.4736 (3)	10.68 (8)
^{60}Co	5.2712 (4) year	1173.228 (3)	99.857 (22)
		1332.492 (4)	99.983 (6)
^{65}Zn	243.66 (9) days	1115.539 (2)	50.60 (24)
^{85}Sr	64.84 (2) days	514.0048 (22)	98.4 (4)
^{88}Y	106.616 (13) days	898.036 (4)	94.0 (3)
		1836.052 (13)	99.36 (3)
^{109}Cd	461.4 (12) days	88.0336 (10)	3.63 (2)
^{113}Sn	115.09 (3) days	391.698 (3)	64.89 (13)
^{137}Cs	30.03 (5) year	661.657 (3)	85.1 (2)
^{139}Ce	137.641 (20) days	165.8575 (11)	79.87 (6)
^{152}Eu	13.506 (6) year	121.7817 (3)	28.37 (13)
		244.6974 (8)	7.53 (4)
		344.2785 (12)	26.57 (11)
		411.1165 (12)	2.238 (10)
		~443.96[g]	3.125 (14)
		778.9045 (24)	12.97 (6)
		867.380 (3)	4.214 (25)
		964.05[g]	14.63 (6)
		1085.837 (10)	10.13 (5)
		1089.737 (10)	1.731 (9)
		1112.076 (3)	13.54 (6)
		1212.948 (11)	1.412 (8)
		1299.142 (8)	1.626 (11)
		1408.013 (3)	20.85 (9)
^{198}Au	2.6956 (3) days	411.80205 (17)	95.58 (12)[f]
^{203}Hg	46.595 (6) days	279.1952 (10)	81.48 (8)
^{228}Th and daughters	1.9116 (16) year	238.632 (2)[e]	43.5 (4)
		583.187 (2)	30.6 (2)
		727.330 (9)[e]	6.69 (9)
		860.564 (5)[e]	4.50 (4)
		1620.735 (10)[e]	1.49 (5)
		2614.511 (10)	35.86 (6)
^{241}Am	432.2 (7) year	26.3446 (2)	2.40 (3)[f]
		59.5409 (1)	36.0 (4)

[a] From Ref. 5, unless otherwise noted.
[b] For conversion from days to years, 1 year is 365.2422 days.
[c] Uncertainty in last digit or digits is shown in parentheses.
[d] Ref. 27, unless otherwise noted.
[e] Ref. 28, unless otherwise noted.
[f] Ref. 3.
[g] In a Ge-detector spectrum, this peak is a multiplet.

Table 16. **Decay Data for Selected Radioisotopes of Interest in Applications**[a]

Radio-isotope	Half-life[a]	Principal γ-rays; E_γ,[a] keV	P_γ,[a] %	Decay energy, keV	Particle type[b]	Average particle energy,[c] keV	Average γ-ray energy,[c] keV
^{75}Se	119.79 (4) days	10.67 K[d]	54.6 (11)	863.4	e^-	14.2	392
					IB	0.029	
		96.7340 (9)	3.42 (3)				
		121.1155 (11)	17.2 (3)				
		136.0001 (6)	58.3 (7)				
		264.6576 (9)	58.9 (3)				
		279.5422 (10)	24.99 (14)				
		400.6572 (8)	11.47 (9)				
^{99m}Tc	6.0058 (12)[e] h (^{99}Mo 2.7 days)	140.511 (1)	89.06 (24)	142.6	e^-	14.2	123.9
^{131}I	8.02070 (11) days	284.305 (5)	6.14 (6)	970.8	β^-	182	382
					e^-	10.04	
					IB	0.113	
		364.489 (5)	81.7 (8)				
		636.989 (4)	7.17 (10)				
^{201}Tl	72.912 (17) h	70.1 K_α[d]	73.8 (15)	481	e^-	48	92
					IB	0.47	
		80.6 K_β[d]	20.5 (7)				
		135.34 (4)	2.565 (24)				
		167.43 (7)	10.00				

[a] Ref. 3, unless otherwise noted. Uncertainty in last digit or digits is shown in parentheses.
[b] The particle notation is β^- for electrons from β^--decay, e^- for internal conversion electrons, and IB for photons from internal bremsstrahlung.
[c] Ref. 24.
[d] X-ray; energy is taken from Ref. 24.
[e] From Ref. 5. Value has been reported to vary by as much as 0.3% as a result of chemical environment.

Table 17. **Radionuclides Useful for Determining the Age of Materials**

Parent	Half-life,[a,b] year	Stable daughter	Natural abundance of daughter,[b,c] %	Intermediate nuclides?
^{14}C	$5.70\ (3) \times 10^{3}$	^{14}N	99.634 (20)	No
^{235}U	$7.04\ (1) \times 10^{8}$	^{207}Pb	22.1 (1)	Yes
^{238}U	$4.468\ (3) \times 10^{9}$	^{206}Pb	24.1 (1)	Yes
^{40}K	$1.248\ (3) \times 10^{9}$	^{40}Ar	99.600 (3)	No
^{232}Th	$1.405\ (6) \times 10^{10}$	^{208}Pb	52.4 (1)	Yes
^{87}Rb	$4.81\ (9) \times 10^{10}$	^{87}Sr	7.00 (1)	No

[a] From Ref. 5.
[b] The uncertainty in the least significant digit(s) is shown in parentheses.
[c] From Ref. 4.

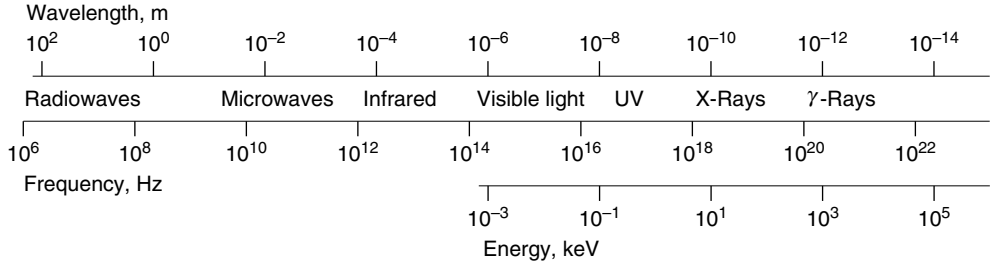

Fig. 1. Electromagnetic spectrum (1).

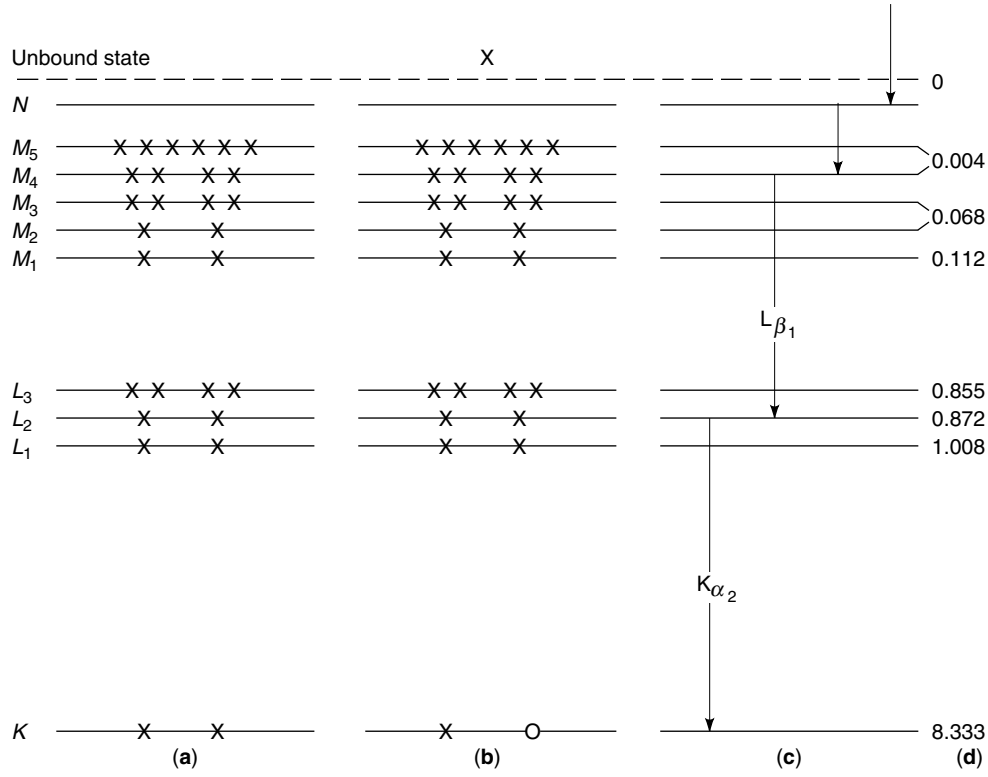

Fig. 2. Energy level diagram, where K–N correspond to electron energy levels for an atom, X to electrons in a particular energy level, and 0 to an empty slot in an energy level (1). Above the dashed line is the unbound state. (**a**) An atom of Ni, 28 electrons, in the lowest energy or ground state; (**b**) an ion of Ni where one electron from the K level has been excited to the unbound state; (**c**) a process by which Ni can return to the ground state where each arrow represents a transition for an electron from one level to another; and (**d**) the energies of the levels in kiloelectronvolts (keV) from which the energy of the emitted X-rays may be calculated.

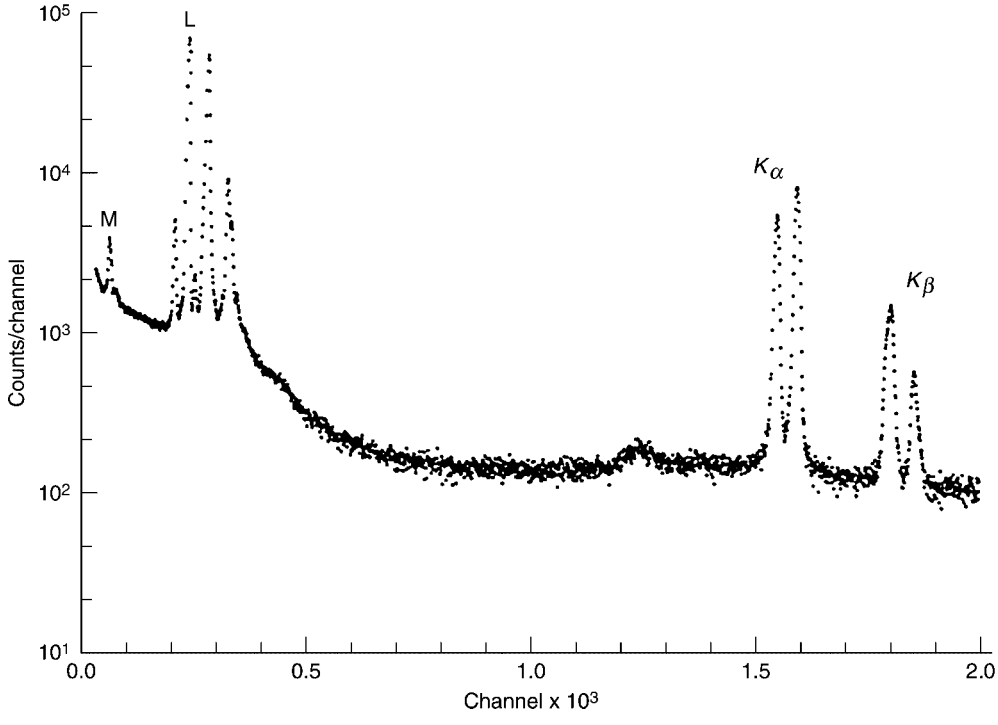

Fig. 3. Photon spectrum, measured by using a planar Ge detector for X-rays emitted in the radioactive β-decay of ^{207}Bi.

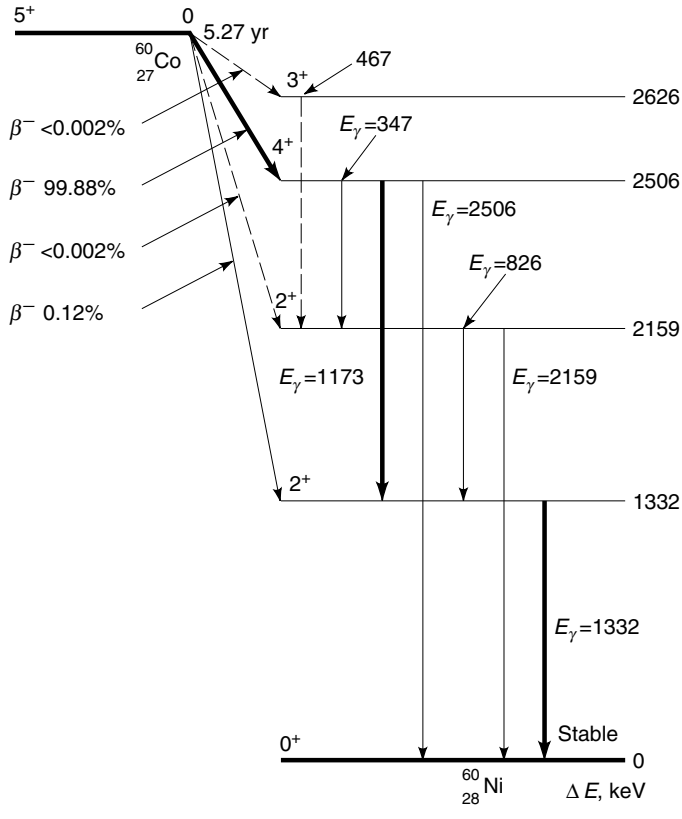

Fig. 4. Decay scheme of ^{60}Co as an example of β^--decay, showing the spins and parities of the levels populated in the daughter nucleus and the energies in keV of these levels, where (→) represents the principal decay mode, (→) an alternative mode, and (−− →) is a highly improbable transition.

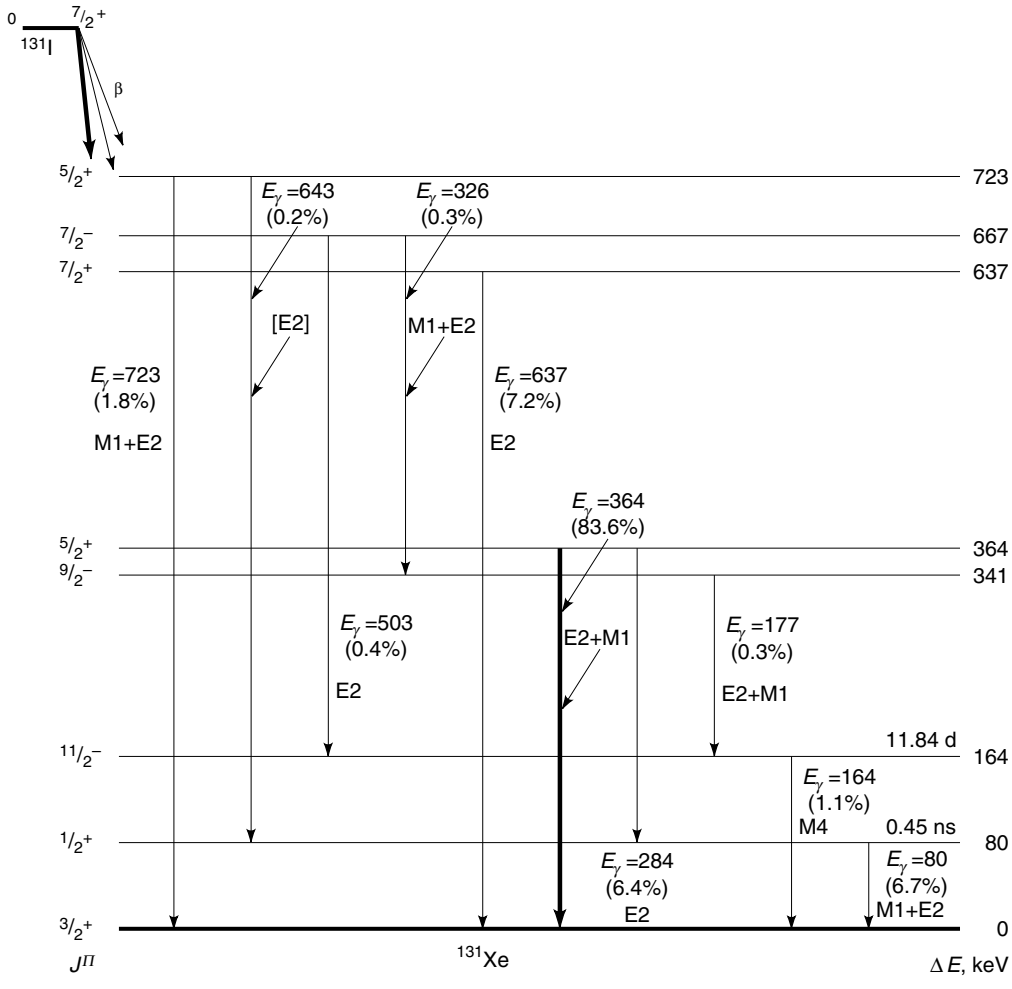

Fig. 5. Decay scheme of ^{131}I, showing the energies, spins, and parities of the levels populated in the daughter nucleus, ^{131}Xe, and the energies in keV, emission probabilities (in %), and multipolarities of the γ-ray transitions. There is a strong dependence of the γ-ray lifetime on the γ-character. The M1 + E2 γ-ray of 177 keV has a half-life of 1.6 ns; the half-life of the 164-keV M4 γ-ray is 1.02×10^6 s.

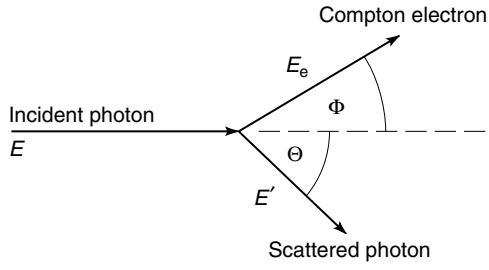

Fig. 6. Schematic illustration of the relationships of the original γ-ray and the scattered radiations for Compton scattering where E is the energy of the incident photon, E_e is the energy of the recoiling electron, and E' is the energy of the scattered photon.