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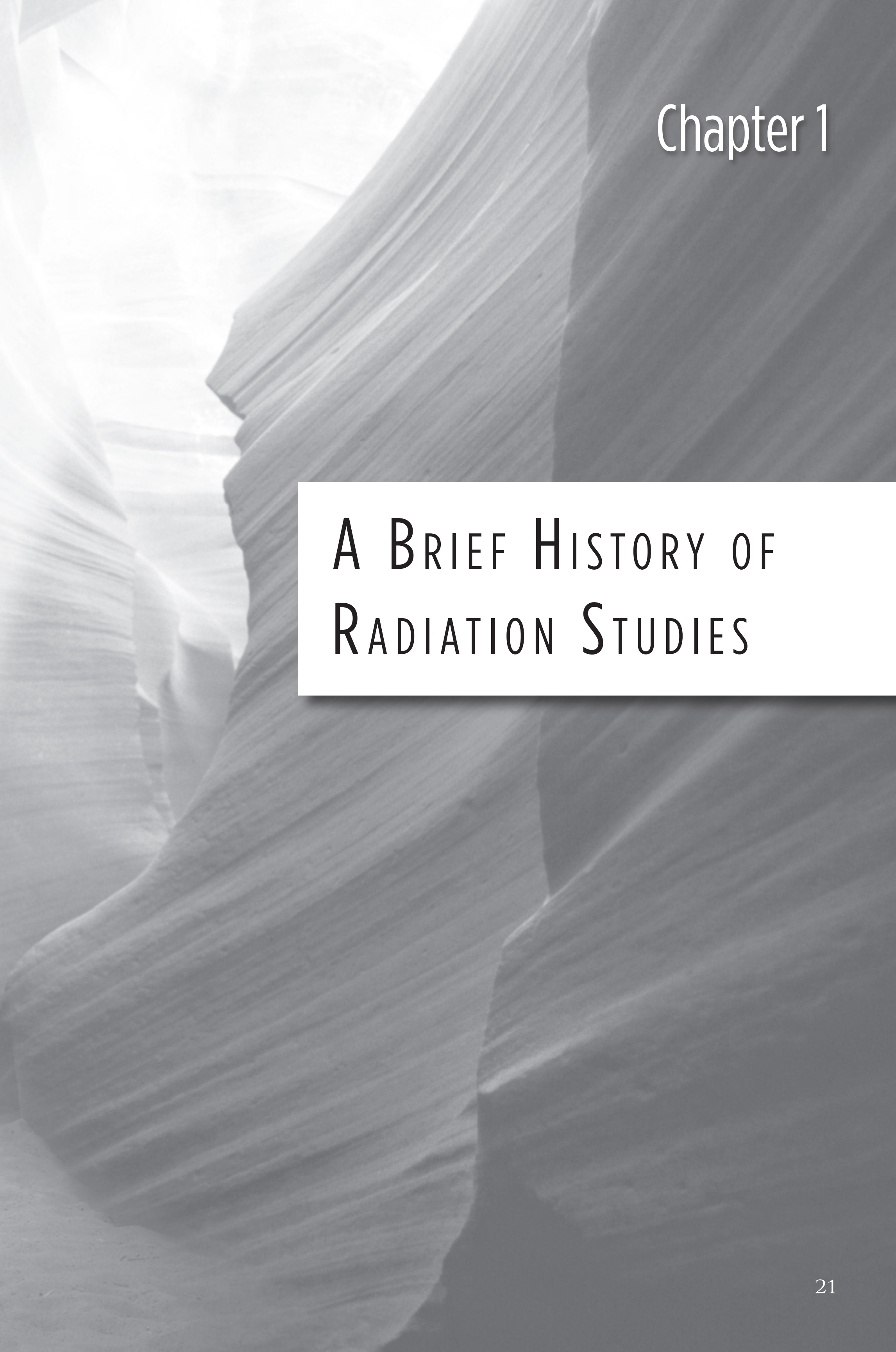

Chapter 1

A Brief History of Radiation Studies

Our story begins just over a century ago in Europe. Several scientists explored the mysterious rays given off by various mineral ores mined from the earth. These invisible rays were observed to remove a build-up of static electricity and they also caused certain materials to fluoresce or glow in the dark. The names of the science pioneers include Henri Becquerel, Frederick Soddy, Ernest Rutherford, Wilhelm Roentgen, J.J. Thomson, Marie Sklodowska Curie, and her husband, Pierre Curie. Each of these eventually received Nobel Prizes for their scientific research.

One of the minerals they studied was a variety of uranium ore commonly called *pitchblende*. It is now known as uraninite with the chemical formula UO_2. Other uranium oxides refined by chemical separation include U_2O_3, UO_3, and U_3O_8. Working in Paris, Henri Becquerel noticed in 1896 that the radiation given off by uranium compounds could fog or darken a photographic plate even when the plate was kept inside its protective cover. Unseen particles emitted by the mineral ore were energetic enough to penetrate the shielding and expose the film.

To help our understanding of the radiation particles, a brief review of chemistry is helpful. There are currently about 115 known elements in the periodic table. Not all printed tables are up to date and the most recent elements have not been verified or named as of this writing. The newer entries are made in the laboratory by colliding known elements. They have very brief lifetimes, typically milliseconds or less. Of the total known elements, 92 occur naturally, the heaviest being uranium. Most of the elements themselves also occur in several varieties called *isotopes*. The Greek roots, *iso* and *topos,* mean "same place" since all the isotopes of a given element are chemically similar and occupy the same space in the periodic table. As an example, there are three naturally occurring isotopes of the element carbon — carbon-12, 13, and 14 (Figure 1-1). These numbers are the atomic weights or masses of the isotopes compared with hydrogen, which is the lightest element. The

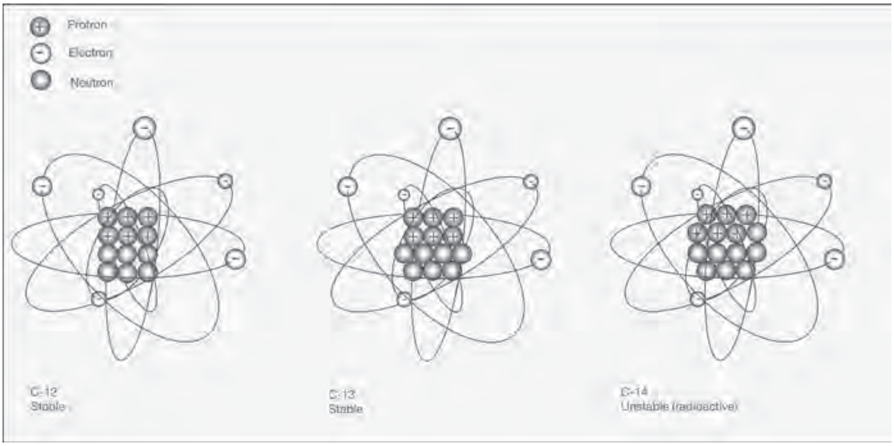

Figure 1-1. An illustration of three varieties or isotopes of the element carbon. The nucleus at the center of each carbon atom always holds six protons; the number of neutrons varies for the different isotopes. Carbon-12 and 13 are stable. Carbon-14 is unstable and radioactive with a half-life of 5,730 years.

carbon-12 atom is by far the most abundant carbon isotope and weighs 12 times as much as hydrogen. The number labels are often written as C-12, C-13, and C-14, or alternately as superscripts, for example ^{12}C, ^{13}C, and ^{14}C.

Each atom of carbon has six protons in its nucleus. The number of protons in an element is known as its atomic number. This is also the number of electrons which orbit the carbon nucleus, although electrons are often shared with other atoms by chemical bonding. Carbon-13 is slightly heavier than carbon-12 because the C-13 variety has one additional neutron in its nucleus, seven instead of the usual six neutrons of carbon-12. Isotopes which possess extra neutrons, such as carbon-14, often are unstable and eventually experience radioactive decay. In this process, the isotope radiates away energy and particles. There are more than 2,000 known isotopes among all the elements. Uranium alone has at least 28 distinct isotope varieties. The majority of all isotopes are radioactive, with a great range of lifetimes from microseconds to billions of years. However, the most common isotopes in nature are stable.

The topic of this book is radioisotope dating which concerns processes within the atomic nucleus. It is helpful to realize the small size of this central portion of the atom. The diameter of a typical atom, out to where the electrons circulate, is about one ten-billionth of a meter. This can be written as 10^{-10} meter, a length known as one *angstrom*. The thickness of a single page of this book is about one million atoms, or one million angstroms. The atomic nucleus is 100,000 times *smaller* than a single angstrom, written as 10^{-15} meter and known as a length of one *fermi* or *femtometer*. Suppose the nucleus of an atom could be enlarged to the size of a baseball. Then the outer electrons would orbit at a distance of about three miles, or five kilometers. This illustration shows that an atom is mostly empty space. The central nucleus is indeed extremely compact, even though it holds almost the entire mass or weight of the atom. Nuclear decay clearly involves the behavior of matter on the very small, sub-microscopic scale.

Early experiments revealed that radiation particles were emitted from within the atom's nucleus. It was discovered that when this occurs a very fundamental alteration also takes place: the original element becomes an entirely different kind of atom. For example, uranium atoms eventually turn into the element lead. Several centuries ago medieval alchemists attempted to change various "base metals" into gold. Today, we know that the process of radioactivity actually performs such transformations. For example, one particular isotope of mercury, Hg-190, decays spontaneously to gold, Au-190. However, this rare form of mercury is even more valuable than the few gold atoms which result from the transition.

Varieties of Radiation

Three major types of radiation have been identified in nature. Ernest Rutherford named them with the first three letters of the Greek alphabet to reflect their elusive, invisible character. In the decades following Rutherford's pioneering work, research unveiled the detailed nature of these mysterious rays. The alpha rays or particles (α) are equivalent to the nuclei (the plural of nucleus) of helium atoms. An alpha particle is a tiny bound packet containing two neutrons and two protons. It carries a double plus electrical charge because of the two positively charged protons. The beta particles (β) are single electrons which carry a negative charge. Electrons are normally bound in orbits around an atomic nucleus and thus are an integral part of every atom. There are multiplied trillions of electrons in our bodies and also in every visible object. Electrons are only called beta particles when they are free from atoms and moving at high speed. Gamma (γ) rays, the third type of radiation, are a form of high-energy electromagnetic radiation. They are a part of the light spectrum with a short wavelength and a high frequency. Gamma rays are invisible to our eyes, similar to x-rays. Light in general displays the dual behavior of both waves and particles. When characterized as particles, the "wave packets" of light, including gamma rays, are called photons. The three types of radiation identified by Rutherford have very different penetrating abilities. This and several other physical properties are listed in Table 1-1. Beyond the α, β, and γ forms of radiation there are several others that can be produced in the laboratory. These include beams of positrons, neutrons, protons, and antiprotons. Each of these has important applications in physics research, technology, and medicine.

Alpha particles are often released during the decay of the heavier radioactive isotopes such as samarium, thorium, and uranium. Beta emission occurs when a neutron within a nucleus spontaneously converts to a proton and an electron. The proton stays behind and the electron is emitted from the nucleus. Gamma rays often accompany both alpha and beta radiation. The gamma radiation provides a way for atoms to release excess energy when nuclear decay occurs.

Table 1-1. The three types of radiation commonly emitted during nuclear decay are called alpha, beta, and gamma. The + and – signs represent the electrical charge of the radiation particles. The letter c stands for the speed of light in a vacuum.

Type of Radiation	Alpha	Beta	Gamma
Greek letter symbol	α	β	γ
Electrical charge	++	-	Neutral
Typical speed c = light speed = 186,000 miles/second = $3x10^8$ meters/second	0.8c	0.99c	c
Particle identification	Helium nucleus	Electron	Light photon
Can be stopped by…	A few inches of air	A few sheets of paper or metal foil	Inches (or feet) thickness of lead

Nuclear Half-life

Early studies revealed a basic property of radioactive decay called *nuclear half-life*. This is the length of time required for 50 percent of a quantity of radioactive material to disintegrate or decay away. Suppose we let an arrow represent one half-life for a radioactive material and we begin with a total of N atoms. Then the remaining or leftover amount of material will decrease as half-life increments of time pass.

$$N \rightarrow N/2 \rightarrow N/4 \rightarrow N/8 \rightarrow N/16 \rightarrow N/32 \rightarrow \dots$$

It is almost as if one keeps slicing the last piece of pie in half with an ever-smaller portion of pie always remaining (Figure 1-2). Notice that in the unusual mathematics of nuclear decay, two half-lives do not equal a whole life. Instead, the passing of two half-lives of