Contemporary Radiobiology

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By

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PREFACE

Japan has an unfortunate history of radiation exposures, such as the A-bomb disaster, fishermen's exposures at the Marshal atolls, the JCO criticality accident at Tokai village, and the unprecedented nuclear power plant accident at the Fukushima Daiichi Nuclear Power Plant, where three nuclear reactors consecutively lost their cooling capacity after the earthquake and tsunami on March 11, 2011. In Fukushima, one hundred forty thousand residents were forced to leave their homes, suffered from anxiety over possible late radiation effects, and also suffered from the loss of their economic communities and their social communities. There are presently plans for more than 50 reactors to be operated in Japan. Worldwide, there are more than 10,000 nuclear weapons, mainly in the United States and Russia, and these present potential sources of harm to mankind. On the other hand, medical diagnoses using radiation are made in 3.65 billion cases each year around the world, and these medical exposures have become a major source of radiation exposures.

The earth was created through the accumulation of material from nuclear reactions that occurred in a corner of the galaxy. Although this nuclear event was about 4.8 billion years ago, radioactive substances from that event are still sources of ground radiation and radon gas in the earth. In addition, recent observations of neutrinos from deep in the earth confirmed that those radioactive substances supply the enormous heat (decay heat) in the earth, in addition to the gravitational energy present at the birth of the earth. This heat moves the continental plates which then causes earthquakes and tsunami, and such events eventually led to disasters such as the accident at the Fukushima Daiichi Nuclear Power Plant. Even today, people are surrounded by natural radiation sources and artificial radiation sources, and it seems like a good idea that they should be able to have a minimum of knowledge about the nature of radiation, its deleterious effects on health, and how we can protect ourselves from radiation.

The reason I decided to write this book was the occurrence of the accident at the Fukushima Daiichi Nuclear Power Plant. In lectures given after the accident, I realized that there should be some information or sources that covered the subject of radiation biology, and which could be shared by lecturers, doctors, researchers, students, administrators, and citizens who were concerned about the use and presence of radiation. For that reason, this book was intended to present the current state of knowledge about radiation for non-experts, and also to describe the latest scientific findings in the fields of radiation molecular biology and medicine. Moreover, because of the initial purpose of this publication, this book also focuses on past nuclear disasters and radiation currently present in our environment. As a result, the contents of the book cover a vast range of subjects going from Chapter 1 (the physics of radiation) to the end of Chapter 15 (nuclear disarmament). These chapters are grouped into five parts, and readers can choose to read the individual sections which they find are of interest to them. Part I describes the “Physical Properties of Radiation” for people whose interests focus on the measurement of radiation, nuclear power plants etc. Similarly, Part II “Radiation and Biology”, Part III “Radiation and Medicine”, and Part IV “Life and Radiation” should be of interest to those who want to learn about the deleterious effects of radiation, the mechanisms involved in the medical use of radiation, and the life sciences and radiation, respectively. If one is interested in past nuclear disasters and radiation protection, Part V “Nuclear Disasters and Radiation Protection” should be of interest. In order to help understand the contents of the book, there are “Commentary” sections related to the material in some of the chapters. In addition, Appendices and “Questions and Answers”are also provided in the book.

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March 11, 2019
Radiation Biology Center, Kyoto University

PART I

PHYSICAL PROPERTIES OF RADIATION

CHAPTER ONE

THE NATURE OF RADIATION

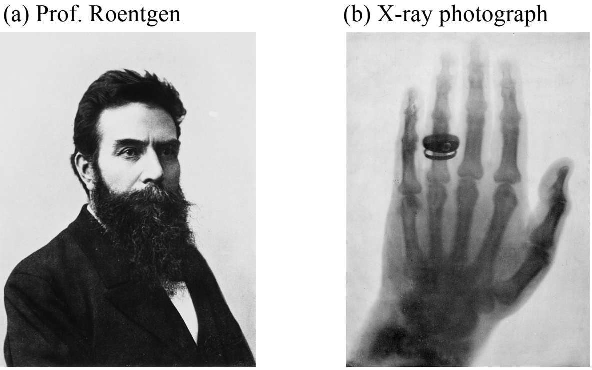
There are different types of radiation: electromagnetic waves such as X-rays and γ-rays, and particle beams such as α-rays and β-rays. All of these different types of radiation can collide or interact with matter and cause ionization and light emission. Therefore, the quantity of radiation can be easily measured with detection instruments capable of measuring ionization and light emission events. Here, we describe the basic properties of radiation, such as ionization, and describe the radiation units used in observing biological effects, and the associated measurement methods.

1.1 The discovery of radiation

1.1.1 Radiation and radioactivity

Radiation is present in our daily lives as part of our natural environment, and is also used for medical and industrial purposes. However, it was only relatively recently that society began to understand and use radiation and, as happend with other scientific findings, this discovery was an accidental event. Wilhelm C. Roentgen, a professor of physics at the University of Wuerzburg (Fig. 1.1a) studied electron beams generated by a Crookes tube with a positive pole (anode) and a negative pole (cathode) (see Chapter 9.1.2). When a high voltage was applied across these poles, Roentgen noticed that fluorescent material located in his lab at a distance from the Crookes tube emitted light or fluorescence, even after the material was covered with black paper. This was due to a new type of radiation which was transmitted through the glass of the Crookes tube. Roentgen first reported this in the Journal of the Wuerzburg Physical Medical Society. The article was "Über eine neue art von strahlen" or “Describing a new type of radiation” and was dated December 28, 1895.

This new radiation was called "**X-rays**" using the symbol X which represented unknown quantities in mathematics. The paper was accompanied by an X-ray photograph of his wife's hand, suggesting that he was thinking about possible medical applications almost immediately after his discovery. Indeed, the usefulness of X-rays in medicine was discussed at a meeting of the Berlin Internal Medicine Society early in the New Year of 1896, and on January 23, Roentgen himself gave a lecture at the Wuerzburg Physical Medical Society. In his lecture, he discussed the ability of X-rays to travel through the human body, and also circulated X-ray photographs of a participant's hand (Fig. 1.1b). This was an exciting discovery, and the discovery of this new type of radiation earned Roentgen the honor of receiving the First Nobel Prize in Physics.



(a) Prof. Roentgen

(b) X-ray photograph

Figure 1.1 Photo of Prof. Roentgen and an X-ray photograph.
(a) A Photo of Prof. Wilhelm Conrad Roentgen at the University of Wurzburg, Germany (Courtesy of U.S. National Library of Medicine). (b) an X-ray photograph of a participant's hand circulated in Roentgen's lecture on January 23, 1896. (Courtesy of the University of Wurzburg).

The following year, in 1896, Antoine H. Becquerel (France) reported that radiation from natural uranium ore has properties similar to X-rays. This new type of radiation was called Becquerel rays and was not initially identified as being X-rays (Commentary 1). As a result of this discovery, Becquerel's name was chosen to represent a unit of radioactivity (see Chapter 1.1.2).

Eventually it was discovered that Becquerel's rays were not a single type of radiation. Based on differing abilities to penetrate different substances, Earnest Rutherford deduced that there were more than two types of radiation present in Becquerel rays, and in 1898 he named them α-rays and β-rays, respectively (Fig. 1.2). Two years later, another researcher found a third type of radiation with a high penetration ability and named this third form of radiation γ-rays following advice from

Rutherford. These α-rays, β-rays and γ-rays are generated through the nuclear decay of radioactive elements (see Chapter 2), and this is a different mechanism from that which generates X-rays.

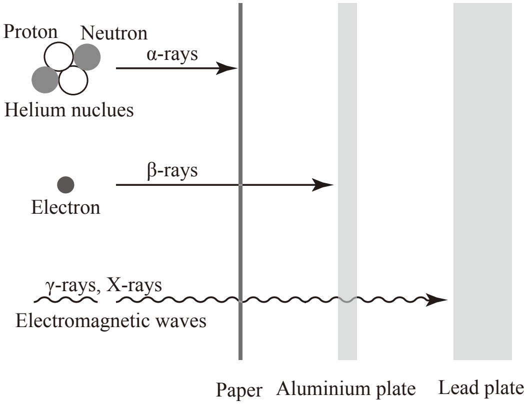


Figure 1.2 Several types of radiation and their penetrating abilities. Although particle beams, including α-rays and β-rays, can be completely shielded by paper or a thin aluminum foil, a thick lead block is necessary to provide a shield against γ-rays or electromagnetic waves.

Commentary 1. Another Poincaré conjecture

Henri Poincaré is a French mathematician and physicist who lived in the latter part of the 19th century. The Poincaré conjecture is famous for being the Millennium Prize Problem which was a major mathematical problem in topology. There was a prize of $1,000,000 for someone who could solve the problem. It was solved by the Russian mathematician, Grigori Perelman, in 2002 after 100 years, but he received a great deal of attention when he refused the prize money. However, from Poincaré's standpoint of emphasizing intuition, he made other predictions besides his famous conjecture.

Another Poincaré prediction was made immediately after a report by Roentgen. At the Institute of France, Poincaré speculated on the possibility that substances which were able to emit fluorescent light also had the ability to emit X-rays along with having fluorescence properties. Bequerel was inspired by this lecture and tried to detect X-rays in fluorescent uranium ore in sunlight. However, he discovered that radiation was emitted in the absence of sunlight. Since this was only two months after the discovery of X-rays, people speculated that there was a fierce research competition between these two people concerning the discovery of radiation. The fact is that the discovery of Becquerel rays was triggered by Poincaré's intuition after a report by Roentgen.

Mrs. Marie Curie (France) was interested in the new radiation discovered by Becquerel, and tried to separate and refine pitchblende ore, which emits radiation similar to that emitted from uranium ore, and reported in 1898 that there were two types of radioactive elements, Polonium and Radium. Polonium was named after Marie Curie's native country Poland, and Radium is the Latin word for radiation. Mrs. Curie also succeeded in developing a method to quantitatively measure the amount of ionization produced by radiation by using a quartz plate piezoelectric meter which was prepared by her husband Pierre. From her studies, it was found that the amount of radiation present was not dependent on the ambient temperature and light, but only on the amount of the radioactive substance present, such as uranium or radium. This was also the first time the word "radioactivity" was used to denote ionization. To discuss radiation, it is necessary to define differences in the meanings of the words radioactivity, radioactive substances (elements), and radiation (such as X-rays). These relationships can be illustrated by comparing these terms with a bonfire (Fig. 1.3).

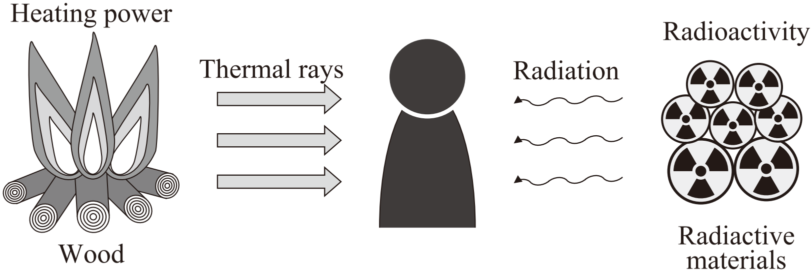


Figure 1.3 Radiation and radioactivity.
Radiation and radioactivity are illustrated by comparisons to a bonfire. The bonfire's power and its (infrared) thermal rays correspond to radioactivity and radiation, respectively.

Radiation consists of electromagnetic waves or particle beams that are generated by either X-ray tubes or radioactive material. It is sometimes referred to as ionizing radiation to distinguish it from electromagnetic waves such as ultraviolet light which does not cause ionization. One can think of radiation as being the equivalent of (infrared) thermal rays emitted from a bonfire. Atoms with a non-neutral charge are called ionized (additional details are shown on Chapter 1.1.2).

Radioactive material or elements are substances or elements that emit radiation, such as Cesium-137. This corresponds to wood which can serve as fuel for a bonfire.

Radioactivity is the ability of a radioactive substance to emit radiation. This corresponds to a bonfire's heat. Thermal rays (i.e. radiation) can cause burns (i.e. radiation injuries), and the burns (i.e. radiation injuries) will be proportional to the bonfire’s heat power (i.e. radioactivity).

The term radioactivity is used to describe the ability to emit radiation, and this is independent of the type of radiation. Also, this term is used to describe radiation from naturally radioactive materials, but not from radiation generators such as X-ray tubes.

1.1.2 Different types of radiation and their penetration abilities

Currently several types of radiation, including α-rays, β-rays, γ-rays and X-rays are known. To understand their properties, a review of the structure of atoms is necessary. In an atom, a negatively charged electron is orbiting around a positively charged nucleus. This electron is referred to as an orbital electron (Fig. 1.4) because electrons can only be present in defined atomic orbits which are described as the K shell, L shell, M shell, N shell, O shell, and P shell. The orbits get larger with each of the sequential letters used to name the orbits. The electrons of the outermost shell are associated with the chemical nature of the atom. For example, Na, K, and Cs belonging to the same congener (alkali metals) in the periodic table, and have only one electron in the outermost M shell, N shell, or P shell, respectively. When these electrons are free or released from the atom, these atoms become positive mono-valent ions, such as Na^+, K^+, Cs^+.

The strength of the positive charge in the nucleus is determined by the number of protons present in the nucleus, so that the proton number for the atom always coincides with the number of orbital electrons unless the atom is ionized (i.e. loses an electron). As the number of protons increases, the atom’s size increases, and there is an increase in the number of outermost electrons. The number of protons will define the physical nature of the atom. Thus, the number of protons is the atomic number which represents the atom. The neutrons present in the nucleus have almost the same mass as the protons, and the total number of protons and neutrons is called the mass number. The atomic number and mass number are expressed as the "mass number (upper row) / atomic number (lower row) and atom name" (Fig. 1.4). For example, cesium present in the environment is represented by ${}^{133}_{55}Cs$ where 133 is the mass number and 55 is the atomic number. Similarly, radioactive cesium is designated as ${}^{134}_{55}Cs$

and $^{137}_{55}$Cs. Although these cesium forms have different mass numbers, such as 133, 134, 137, the atomic numbers are all 55, indicating that they are all the same element cesium. Conventionally, the atomic number 55 is often omitted. When atoms have the same number of protons but different mass numbers, they are called isotopes, and are described by terms such as Cesium-137. When isotopes are radioactive, such as Cesium-134 and -137, they are called **radioisotopes**. Conversely, nonradioactive isotopes, such as Cesium-133, are called stable isotopes.

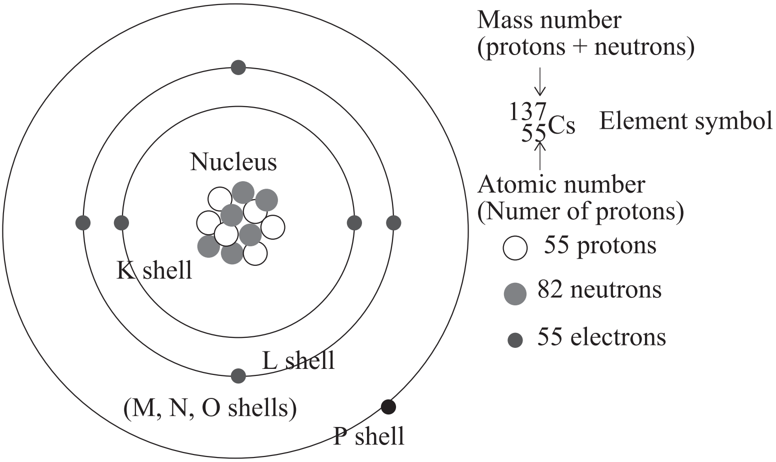


Figure 1.4 Nuclear model of Cesium-137.
The nucleus of a Cesium-137 atom consists of 55 protons, 82 neutrons and 55 orbital electrons, including 1 electron in the outermost P shell.

When protons and electrons or nuclei are accelerated to a high speed, they behave as radiation. The **α-rays** discovered by Rutherford were high-speed helium nuclei. The helium nucleus is a large particle composed of two protons and two neutrons. Thus, the helium nucleus is bulky in terms of size and charge, so a helium atom α-ray interacts frequently with a nucleus in target substances and loses all its energy in a short distance. For this reason, an α-ray cannot penetrate human skin and is easily shielded by a piece of paper (Fig. 1.2). On the other hand, **β-rays** are high-speed electrons. An electron is one of the elementary particles which are the components of an atom, and its mass is about 1/1800 of a proton. Since electrons are much smaller than helium nuclei, they can penetrate matter much more effectively than α-rays. For that reason, β-rays can require several mm of aluminum foil to shield a target (Fig. 1.2). However, β-rays cannot reach deeper parts of the body although they can penetrate human skin. Neutrons and proton particles accelerated to a high velocity are called neutron beams and proton beams, respectively. Like α-rays and β-rays, neutron beams and proton beams are generally called **particle beams**.

When radionuclides decay through the emission of α-rays or β-rays, additional energy remaining in the nucleus can be released as γ-rays. **γ-rays** are electromagnetic waves, like light and ultraviolet light rays, but they have a tremendous amount of energy. They can cause ionization by ejecting orbital electrons in atoms when they interact with matter. Thus, γ-rays originate during the decay of a nucleus, whereas X-rays are produced by electrons originating outside of the nucleus, but they are both electromagnetic waves. When ionization occurs through the ejection of electrons in the inner orbits, electrons from the outer atomic orbits can occupy these vacant inner orbit positions. The energy difference between inner orbit electrons and outer orbit electrons is released in the form of X-rays (Fig. 1.5a). This type of X-ray is called a “characteristic X-ray”, which has a specific energy corresponding to the differences in the orbital energies in a specific atom (Fig. 1.5b).

However, the X-rays originally observed by Roentgen were **bremsstrahlung X-rays** which are generated through a different mechanism than characteristic X-rays (Fig. 1.5a). When electrons are released from the high voltage cathode in a Crookes tube, they are pulled to the positively charged nuclei of the molecules which compose the glass tube, and are decelerated by a braking mechanism (bremsstrahlung). These decelerated electrons have a reduced kinetic energy and emit their lost energy as electromagnetic waves (i.e. as bremsstrahlung X-rays). Unlike characteristic X-rays, bremsstrahlung X-rays are characterized by a continuous energy distribution (Fig. 1.5b). Although X-rays generated from a Crookes tube are only bremsstrahlung X-rays, both characteristic X-rays and bremsstrahlung X-rays are generated from high voltage X-ray generators like the Coolidge tube currently in use. There are essentially no differences in the physical properties between X-rays (characteristic X-rays and bremsstrahlung X-rays) and γ-rays except for the mechanism which generates them. Since both γ-rays and X-rays are high energy electromagnetic waves, they have a much higher ability to penetrate matter than particle beams such as α-rays and β-rays, and are capable of penetrating the human body (Fig. 1.2).

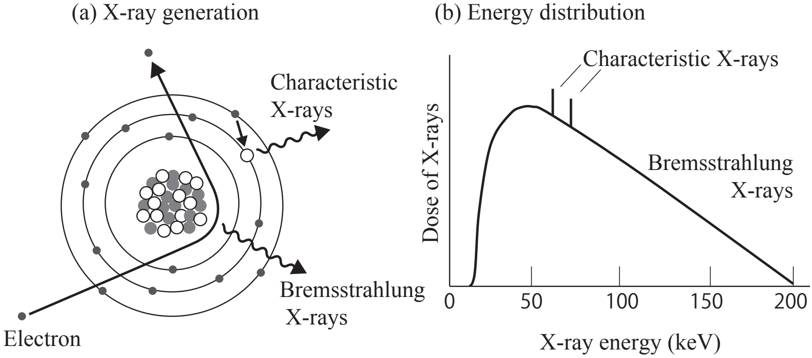


Figure 1.5 X-ray generation from electron collisions.
X-rays generated by electrons colliding with matter are classified into two types of X-rays according to the mechanism involved: (a) Bremsstrahlung X-rays are generated by the deceleration of electrons, and characteristic X-rays are generated when external orbital electrons transit into an empty inner orbital position. (b) Bremsstrahlung X-rays show a continuous energy spectrum, but the energy of characteristic X-rays are called eigenvalues which correspond to the energy difference between the two electron orbits.

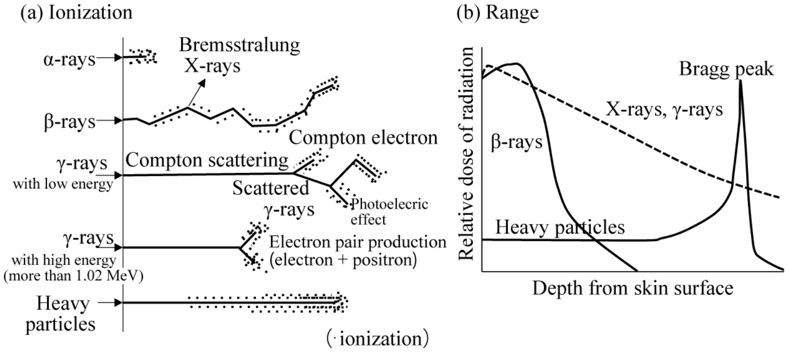
1.2 Mechanisms of ionization and radiation units

1.2.1 How radiation causes ionization

When radiation collides with or interacts with matter in its path, it can gradually lose energy and eventually dissipate. During this process, the radiation can cause ionization and excitation events in the molecules it interacts with, although the detailed aspects of ionization differ between electromagnetic waves and particle beams. Since all radiation damage to the human body originates from these ionization events, a more detailed examination of these events is warranted.

The processes through which electromagnetic waves such as X-rays and γ-rays lose energy in matter are classified into three types: the photoelectric effect, Compton scattering, and electron pair production. In the **photoelectric effect** an X-ray or γ-ray interacts with matter, causes the release of orbital electrons in an atom (thus generating ionization events), and is completely absorbed (photoelectric absorption). The amount of X-ray and γ-ray energy expended during the ionization action is usually 5 to 30 eV (electron volts), and the remainder of the energy provides the kinetic energy of the emitted electrons (called photoelectrons). An eV (electron volt) is a very minute energy unit used to describe the energy present in atoms and electrons (1 eV = 1.60 × 10^{-19} Joules). One eV is defined as the amount of energy given to one electron with a voltage of 1 V (volt). For example, the electron energy generated in an X-ray tube with a voltage of 1000 V is 1.0 keV (or kilo-eV). The energy at which the photoelectric effect occurs varies with the material. For example, the energy of X-rays and γ-rays at which the photoelectric effect occurs with aluminum or lead is 50 keV and 500 keV, respectively.

In the photoelectric effect, the radiation itself is absorbed. X-rays and γ-rays with higher energies, such as 50 keV or more in aluminum, can cause ionization, although the energy will not be entirely delivered to the electrons. After the first interaction, X-rays and γ-rays will have lost some energy, but are still able to undergo subsequent secondary interactions with other atoms, causing sequential ionization events (**Compton scattering**). Electrons generated during these events are called Compton electrons (Fig. 1.6a). As the energy diminishes during this Compton scattering process, the photoelectric effect will finally take place and the radiation's energy will be fully absorbed. Electrons (both photoelectrons and Compton electrons) generated by the photoelectric effect and Compton scattering will continue to collide with other atoms, so that the chain of events can describe a complex pattern. In addition to ionization, fluorescence is also emitted through the excitation of atoms during this process. This is the fluorescence Roentgen observed in a substance placed at a distance from his X-ray tube.


(a) Ionization

(b) Range

Figure 1.6 Ionizing mechanisms and their ranges.
(a) γ-rays gradually lose energy while penetrating matter and undergoing ionizing events, such as electron pair production, and Compton scattering or the photoelectric effect. α-rays and heavy particle beams follow a straight path and

cause ionization, and are finally absorbed by losing their energies in the material they are traversing. β-rays also undergo repeated collisions and cause ionization while generating bremsstrahlung X-rays. (b) Radiation usually will not travel completely through a target, and will be absorbed when it loses all of its energy. α-rays and β-rays gradually lose their energy, while heavy particle beams stop at a certain specific distance from the surface of the skin forming a Bragg peak.

High energy γ-rays with energies over 1.02 MeV (mega-electron volts or one million electron volts) can produce both**,** negatively charged electrons and positively charged positrons, in the vicinity of the nucleus simultaneously, and this is described as **electron pair production**. Since the positron is unstable, it immediately decays, emitting two γ-rays with energies of 0.51 MeV (i.e. annihilation radiation) (Fig. 1.6a). The absorption of radiation energy during these processes tends to increase as the atomic number of the target substance increases. For this reason, lead or elements with a high atomic number are usually used for shielding from X-rays and γ-rays (Fig. 1.2).

Particle beams, such as α-rays and β-rays, collide with atoms and cause ionization and excitation. Repeated subsequent interactions with additional atoms weakens or leads to the absorption of their radiation energy. During this process, particles with small masses, such as β-rays, can have their path altered or bent by the electric field of the nucleus, and generate bremsstrahlung X-rays, and gradually lose energy (see above). Conversely, particles with large masses, like α-rays, travel linearly along their path, so that the generation of bremsstrahlung X-rays is usually not significant (Fig. 1.6a). A high velocity beam of particles which have an atomic number larger than helium is called a heavy particle beam, for example a beam composed of iron ions. Heavy particle beams cause high density ionization tracks to form along their paths and quickly lose all of their energy. Consequently, heavy particle beams stop after a constant distance, and the ion density along their track reaches a notable maximum near the end of the track (this is called the **Bragg effect** and is illustrated in Fig. 1.6b).

In contrast to heavy particle beams, β-rays are gradually attenuated along their path during their penetration of a target, so their ionization track is gentle and uniform when compared to the ionization tracks of heavy particle beams (Fig. 1.6b). In neutron beams, the neutrons have no charge, and hence lose energy through collisions with nuclei rather than with orbital electrons. Since the mass of a hydrogen nucleus is the same as a neutron, the collision of a neutron with a hydrogen nucleus reduces its radiation energy most efficiently. Hence, water is appropriate for use as a neutron shield (see Chapter 2.2.2).

1.2.2 Radioactivity and radiation units

Various units are used to measure radiation and radioactivity, and the units which are used depends on what purpose these measurements are being used for. These measurements could be used to study radiation protection, radiation therapy, environmental decontamination, etc., and the amount of radiation and radioactivity present must be quantified. Although these units, in theory, represent the number of calories of radiation energy absorbed per unit weight and the weight of radioactive substances, respectively, specific defined units, such as the Gray, Sievert or Becquerel, are most convenient to describe specific properties of radiation. These units were named after the physicists Louis H. Gray (UK), Rolf M. Sievert (Sweden), and Antoine H. Becquerel, all of whom made important contributions in the early history of radiation research.

The **Gray** is a unit used to define the amount of radiation absorbed (the absorbed dose) when 1 Joule (J) of energy is absorbed per kg of substance, and this measure can be used in the study of living organisms. The Gray is represented by the symbol Gy (Table 1.1). One hundredth of a Gray or a cGy (centi-gray) can be used as a convenient unit, because it is easy to convert the cGy unit to a rad in the CGS unit system which was used in biological research papers before the Gy became widely used (1 rad = 1 cGy). Even when various targets are exposed to the same absorbed dose in Gy, the biological effects of radiation can still be different depending on the specific type of radiation which is incident, and the specific tissues or organs which receive the radiation. The equivalent dose and effective dose are calculated by multiplying the dose in Gy by specific coefficients, and these doses are used in working with radiation protection. A **Sievert** is used for both the equivalent dose and effective dose, and is represented by the symbol Sv. The relationship between the **equivalent dose** (Sv) and the Gray (Gy) is:

$$\text{Equivalent dose (1 Sv)} = 1\ \text{Gy} \times \text{Wr}$$

where Wr is a radiation weighting factor.

The radiation weighting factor Wr is a coefficient which is determined by the type of radiation involved. For example, Wr is 1.0 is for γ-rays and β-rays, and 20 for α-rays. Other energy-dependent coefficients are used for neutron beams whose quality can vary with the neutron energy (Table 1.1). Since the radiation weighting factors for γ-rays and β-rays are 1, the absorbed doses in Gy have the same numerical values as the equivalent doses in Sv.

Unit	Definition	Purpose
Radiation dose Gy (Gray)	A unit of an absorbed radiation dose when 1 kg absorbs an energy of 1 Joule (about 0.24 calorie)	This unit is used in basic physical studies, biological experiments and radiation therapy.
Sv (Sievert) ・Equivalent dose	Radiation dose unit representing radiation effects in humans. The dose in Gray is multiplied by a radiation weighting factor Wr (Gy × Wr). Wr values for X-rays, γ-rays, and β-rays are all 1. Wr values are 20 for α-rays, respectively.	This unit is used in describing radiation protection and in evaluating radiation effects on the human body which vary with the type of radiation.
・Effective dose	The sum of the total of the doses delivered to specific tissue targets. This dose is multiplied by a tissue weighting factor Wt for each tissue. Wt values for specific tissues are 0.12, 0.08 and 0.01 for bone marrow, gonads and skin, respectively.	This unit is used for legal regulations and in radiological protection to provide an evaluation of the radiation's effect on the whole body when only a specific tissue is exposed.
Radioactivity Bq (Becquerel)	The number of atomic decay per second.	The Becquerel is the product of the decay rate and the number of atoms, so it is proportional to the amount of a radioactive substance which is present.
Quality of radiation LET (Linear energy transfer)	The amount of energy (keV/μm) that is transferred to a target when the radiation traverses a unit distance. The LET value is 0.2-2.0 keV/μm for Cobalt 60 γ-rays and X-rays, and 110 keV/μm for 4 MeV α-rays.	α-rays and heavy particle beams that produce dense ionization have a high LET value, and lead to large biological effects, while X-rays and β-rays with low LET values produce smaller effects

Table 1.1 Units used for radiation

The equivalent dose × Wt is calculated for each tissue, and the sum of all of the individual doses to each of the exposed tissues is the **effective dose**:

Effective dose (in Sv) = Σ (sum of equivalent tissue doses ×Wt)

Where Wt is a tissue weighting factor for each tissue and Σ is the sum of the individual equivalent doses delivered to each tissue.

The dose unit used for writing legal regulations or for writing laws is the effective dose, which is the equivalent dose multiplied by the tissue weighting factor Wt. The tissue weighting factor is a coefficient obtained by apportioning the radiation risk for each tissue in order to evaluate the effect of radiation on the whole body when a specific tissue is exposed (Table 1.1). For example, the specific Wt factors are 0.01 and 0.12, for skin and bone marrow, respectively. The total sum of the individual tissue weighting factors for each tissue adds up to 1 for the entire organism. Since both the equivalent dose and the effective dose are described by the Sievert or Sv unit, it is necessary to pay attention to precisely which dose is referred to when the dose is described in Sieverts (Sv). Small doses can be described using mSv or millisieverts which correspond to 1/1000th of a Sievert, and in microsieverts (μSv) which correspond to 1/1,000,000 of a Sievert. In addition, the dose delivered in a unit of time, such as an hour or minute, is described by the **dose rate** and is expressed in μSv/hr or μSv/min. For example, if one is exposed for 8 hours a day to a dose rate of 10 μSv/hr, the total dose is caluculated as 10 μSv/hour × 8 hours × 365 days = 29.2 mSv in one year. However, a practical effective dose description which is used in radiation protection work is the 1 cm dose equivalent (in Sv) which is used to describe the dose at a depth of 1 cm below the body's surface (where the exposure is maximum) when discussing exposures to X-rays or γ-rays. Because the 1 cm dose equivalent always has a value higher than the equivalent dose and provides a conservative (if slightly overestimated) radiation exposure estimate, radiation dosimeters (e.g. survey meters) indicate the 1 cm dose equivalents.

Because the Gy describes the energy absorbed per unit weight, a conversion to calories is plausible. For example, half of the people irradiated with 4 Gy (= 4 J/kg) in a whole body exposure will die within 60 days (see Chapter 5.3.1), but the total thermal energy absorbed by the whole body (60 kg) is

$$4\ (\mathrm{J/kg}) \times 60\ (\mathrm{kg}) = 240\ (\mathrm{J}) = 57.6\ (\mathrm{Cal})$$

57.6 Cal (calories) can lead to an increase in body temperature of merely 0.00096°C, and this is the same effect one would see from drinking a small spoon full (2.5 ml) of hot water (60°C). Consequently, although the absorbed caloric radiation energy is negligible, there is a still a sufficient amount of energy to ionize and subsequently cleave molecular bonds in any region along the radiation track (path).