Chapter 1
Introduction

1.1 History of Nuclear Technology

The development and utilization of nuclear energy and nuclear radiation began in the late 1930s, which deepened the understanding of nuclear radiation and its interactions with materials. Applications of such knowledge to modern scientific and technological research, to explore new fields, interpret new phenomena, and confirm new substances, gradually generated an emergent branch of science and technology with rich connotations and cross-fertilization with multiple disciplines, namely nuclear science and technology or nuclear technology for short. The build-up of nuclear technology is a milestone in the history of human civilization in the twentieth century and one of the significant symbols of social modernization.

Nuclear technology, an important component of modern science and technology, is one of the most significant cutting-edge technologies in contemporary times, widely used in many fields, such as national defense, scientific research, industry, agriculture, medicine, communication, transportation, environmental protection, archaeology, resource development, space exploration, etc. Nuclear technology is a relatively independent and complete research and application system, behaving the characteristics of knowledge-intensity, cross-penetrating, irreplaceability, high efficiency, and wide adaptability. Nuclear technology has been embraced in the arena of the global high-tech competition as the driving force for the innovative development of new technologies, materials, and methods, and global economic growth.

Nuclear technology is generally composed of nuclear weapons technology, nuclear power technology, and isotope and radiation technology (also known as non-power nuclear technology). The scope of this book is controlled within radiation technology, including radionuclide preparation, nuclear analytical techniques, nuclear instrumentation, radiation processing, and the application of nuclear technology in medicine, agriculture, environment, etc., and peaceful usage of nuclear energy.

Following the first discovery of the radioactivity of uranium salts, French scientists Pierre and Marie Curie discovered polonium (Po) and radium (Ra) in 1898 and refined

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0.1 g of radium salts and a few milligrams of polonium in 1902. The discovery of radium caused revolutionary changes in science and philosophy, which opened the door to explore the mysteries of the atomic world. The following events laid scientific foundations for the birth of nuclear technology and contributed to the rapid development of its applications.

- In 1898, E. Rutherford deflected uranium radiations with a strong magnet and found that at least two types of radiation in opposite directions were present: one is readily absorbed and termed α-radiation, the other one is penetrative and termed β-radiation. In 1900, Paul Villard observed that besides α- and β-radiation, there was a third type of radiation emitted by radium which was unaffected by magnetic fields and termed γ-radiation.
- In 1930, German physicists E. Bothe and H. Becker found mysterious radiation emitted from beryllium, lithium, and boron nuclei bombarded with α-particles, which were of strong penetration ability, and discharged a counter. In 1932, British physicist J. Chadwick argued that this "radiation" consisted of particles of mass nearly equal to that of a proton and with no net charge, termed neutron. After that, the neutron became an important tool for scientists in nuclear science, promoting the rapid development of nuclear science and technology.
- Around 1930, British physicists J. D. Cockcroft and E. T. Walton built the first particle accelerator.
- In 1931, American physicist R. J. Van de Graaft built an electrostatic accelerator, and American physicists E. O. Lawrence and M. S. Livingston designed and built the first cyclotron for accelerating ions. With the development of microwave technology, the traveling wave electron linear accelerator and the standing wave proton accelerator were built in 1947.
- In 1934, Joliot Curie and his wife discovered the artificial radioactivity by bombarding aluminum foil with α-radiation from polonium for the first time, and chemically extracted ^{30}P from the radioactive foil. In the consequent experiments, they found that uranium fission produced multiple neutrons and released large amounts of energy, predicting the feasibility of a nuclear chain reaction.
- In 1938, H. A. Bethe and F. V. Wetabckor independently discovered the fusion reaction, termed "thermonuclear reaction", respectively.
- In 1939, Austrian physicist L. Meitner and her nephew O. Frisch, et al., discovered the phenomenon of nuclear fission of uranium and measured fission energy of around 200 meV.
- In January 1942, Italian-American physicist E. Feimi designed and built the first uranium fission reactor, CP-1 (Chicago Pile 1) in a small courtyard under the west bleachers of a long-abandoned football stadium at the University of Chicago.
- On December 2, 1942, the first natural uranium-graphite reactor successfully started up, achieving the self-sustaining fission chain reaction for the first time.
- At 5:30 a.m. on July 16, 1945, the United States exploded the first atomic bomb in the world for the atomic bombing tests.
- On December 20, 1951, the United States used the surplus heat from its first plutonium-producing breeder reactor to generate electricity at 100 kW.

- On November 1, 1952, the United States exploded the world's first hydrogen bomb on the Coral Island (Marshall Islands) in the Pacific Ocean.
- On January 21, 1954, Nautilus, the first nuclear-powered submarine built in the United States, was launched.
- On June 27, 1954, the Soviet Union built up the world's first nuclear power reactor for electricity with nuclear fuel as electrical power of 5000 kW.
- In 1957, Raychem first produced heat shrinkable materials with accelerator irradiation, creating the history of the radiation chemical industry.
- In 1957, Firestone in the United States made the first use of accelerator irradiation curing technology to produce automotive tires.
- In 1961, Allis-Chalmers and William Myers put the first commercial Anger camera into service at Ohio University.
- On July 21, 1969, the U.S. spacecraft Apollo 11 landed on the moon, heat supplied with two ^{238}Pu (plutonium-238) isotope heaters.
- In 1969, British engineer G. N. Hounsfield successfully designed a computed tomography (CT) instrument, it was introduced in 1972 and promoted the development of nuclear medicine. With the help of CT, doctors improved the detection rate and diagnostic accuracy of lesions.
- In 1970, Ford in the United States used the electron accelerator in curing paint on auto parts for the first time.
- In 1974, the first positron emission computed tomography (PET) scanner was developed, and it was used in clinics in the late 1990s.
- In 1976, John Keyes developed the first multipurpose single-photon emission computed tomography (SPECT) scanner.
- In 1981, J. P. Mach carried out the first single antibody radiopharmaceutical for tumor imaging.
- In 1991, Cytogen first launched a single antibody radiopharmaceutical with FDA clearance for tumor imaging.
- In 2012, the Higgs boson was discovered with the Large Hadron Collider (LHC), which won the 2015 Nobel Prize in Physics.
- In 2015, the Laser Interferometer Gravitational-wave Observatory (LIGO) directly detected gravitational waves for the first time, winning the 2017 Nobel Prize in Physics. □

1.2 Definition, Basic Concepts, and Terminology

1.2.1 Nuclear Technology

Nuclear technology is a comprehensive modern science and technology, based on nuclear physics, radiation physics, radiochemistry, radiation chemistry, and the interaction between nuclear radiation and matter, with accelerators, reactors, nuclear weapons devices, nuclear radiation detectors, and nuclear electronics as supporting technologies. Nuclear technology utilizes the physical, chemical, and biological effects resulting from the interaction of ionizing radiation from radiation sources (including radiation devices and radioisotope sources) and other forms of radiation with matter, to observe natural phenomena, reveal natural laws, solve scientific problems, and apply them in practice.

Nuclear technology covers a wide range of disciplines and applications. In terms of the predominantly adopted technology, it is divided into radiation technology, isotope technology, and supporting technology. Radiation technology encompasses radiation processing, ion beam processing, nuclear analysis technology, nuclear imaging technology, and radiation detection instrumentation. Isotope technology encompasses isotope preparation technology, isotope products, radiopharmaceuticals, radiological chronology, radioisotope power, and isotope tracing technology. Supporting technology encompasses accelerator technology, reactor technology, nuclear radiation detection, nuclear electronics, radioactive source technology, radiation dosimetry, and radiation protection. In terms of application, nuclear technology can be divided into nuclear technology in the industry, nuclear technology in life sciences, nuclear technology in agriculture, nuclear technology in environmental science, nuclear technology in materials science, nuclear technology in energy/electricity, and nuclear instrumentation.

Summarily, during the development of nearly a hundred years, nuclear technology has infiltrated into other basic disciplines, which spawned generating some newly interdisciplinary or marginal disciplines such as nuclear astronomy, nuclear archaeology, nuclear geology, etc.

1.2.2 Elements, Isotopes, and Nuclides

Element: A collective term for a class of atoms with the same number of protons. For example, the element hydrogen (H) is the collective name for the atoms having one proton in the nuclei, including ^{1}H (protium with no neutron, H), ^{2}H (deuterium with one neutron, D), and ^{3}H (tritium with two neutrons, T).

Radioactive element: An element in which all isotopes are radioactive, such as the elements uranium (U), and plutonium (Pu).

Natural radioactive element: A natural element in which all isotopes are radioactive, such as the element uranium (U).

Isotope: A class of nuclides with the same atomic number but different mass numbers. It is a mutual term for the atoms with the same proton number and different neutron numbers. For example, ^{1}H, ^{2}H, and ^{3}H are isotopes of each other.

Isotopic composition: The atomic percentage of each isotope in an element. For example, the isotopic composition of the element lithium (Li) is 7.59% of ^{6}Li and 92.41% of ^{7}Li.

Stable isotope: The non-radioactive isotopes of an element. For example, ^{1}H (protium, H) is the stable isotope of the element hydrogen (H).

Radioisotope: A radioactive isotope of an element or an unstable isotope is an element that undergoes decay or spontaneous fission accompanied by radiation. For example, ^{3}H (tritium, T) is a radioisotope of the element hydrogen (H).

Isotopic abundance: The atomic ratio of a particular isotope to the total atoms in the isotopic mixture of an element. For example, the isotopic abundance of ^{1}H is 99.985%, and that of ^{2}H is 0.015%.

Natural abundance: The measure of the average amount of a given isotope naturally occurring on Earth. For example, ^{1}H abundance of 99.985% refers to its natural abundance.

Enrichment factor: The ratio of the abundance of a particular isotope in an isotope mixture to its natural abundance. For example, for the uranium fuel with 20% ^{235}U used in the nuclear power industry, the enrichment factor of ^{235}U is about 28 (0.72% natural abundance of ^{235}U).

Nuclide: A class of atoms characterized by the specific mass number, atomic number, and nuclear energy state, whose average lifetime is long enough to be observed. It is a collective term for all known isotopes, including stable nuclides (279) and unstable nuclides (about 2700), such as the ^{1}H-nuclide, ^{2}H-nuclide, and ^{3}H-nuclide in the element hydrogen.

Radionuclide: Another term for radioisotope, radioactive nuclide, or unstable nuclide that spontaneously emits alpha, beta, and other radiations. For example, the ^{3}H-nuclide is a radionuclide of the element hydrogen.

Radioactivity: The nuclear property of some nuclides, which spontaneously emit particles or γ-radiation, capture orbital electrons, and emit X-rays, or spontaneously fission. For example, ^{3}H-nuclide spontaneously emits β-rays with energy of 18.5866 keV, i.e., the ^{3}H-nuclide is radioactive.

Natural radioactivity: The radioactivity of a natural nuclide.

Artificial radioactivity: The radioactivity of an artificial radionuclide, also termed induced radioactivity.

Primordial radionuclide: The initial radionuclide with long half-lives that were present at the birth of the Earth and have not yet decayed completely, such as ^{40} K, ^{235}U, ^{238}U, and ^{232}Th.

Cosmogenic radionuclide: The radionuclide produced by the interaction between cosmic radiation and the atomic nuclei in the atmosphere.

Artificial radionuclide: The radionuclide produced by artificial means.

Long-lived radionuclide: The Radiological Protection Ordinance defines a radionuclide with a half-life of more than 100 days as a long-lived radionuclide.

Short-lived radionuclide: The radiation protection Ordinance defines a radionuclide with a half-life of up to100 days as a short-lived radionuclide.

Isomeric state: A metastable excited state of a nucleus with a long enough average lifetime to be observed.

Nuclear Isomer: A nuclide that has the same number of neutrons and protons but in different energy states and rates of radioactive decay.

Isomeric transition: The transition of a nucleus from a metastable isomeric state to a lower energy state (usually the ground state) while emitting γ-radiation.

1.2.3 Basic Quantities and Concepts

Activity/Radioactivity: Also termed as decay rate, defined as the average decaying number of a given number of radionuclides per second, quantifying the number of radionuclides with a unit of Becquerel or Bq. 1 Bq means a radioactive nucleus decays once per second. Another common unit for radioactivity is Curie (Ci), and 1 Ci $= 3.7 \times 10^{10}$ Bq.

Absorbed dose: The total amount of ionizing radiation energy absorbed by a unit mass of material, with the SI unit of J kg^{-1} or Gy. 1 Gy represents one Joule of ionizing radiation energy absorbed per kilogram of material, 1 Gy = 1 J kg^{-1}.

Absorbed dose rate: The absorbed dose per unit time with a unit of Gy s^{-1} or Gy h^{-1}, etc.

Equivalent dose/Dose equivalent: Used to assess how much biological damage is expected from the absorbed dose of a certain type of radiation and is defined as the absorbed radiation dose in an organ or tissue corrected by a radiation weighting factor. Dose equivalent = (Absorbed dose) $\times$ (weighting factor). The SI unit of equivalent dose is J kg^{-1}, or Sievert (Sv), the name it was given to replace the conventional unit of rem (roentgen equivalent in man, 1 Sv = 100 rem).

Nuclear transition: The process by which a nuclear system changes from one quantum energy state to another. Examples include the transition from one nuclide to another through α or β decay or changing the nuclear energy level of a system through the absorption (or emission) of photons, orbital electrons, or electron pairs.

Nuclear magnetic resonance (NMR): The resonance phenomenon resulting from the radiofrequency radiation absorbed by a substance in a magnetic field. For the magnetic moments of atomic nuclei spinning into a magnetic field, only those in some definite directions are allowed, with the energetic differences between them related to the magnetic field. Resonant absorption occurs when the energy of the RF quanta happens to equal such energetic differences, resulting in energy level transition and the orientation deflection of the magnetic moments.

Nuclear energy: The energy released during a nuclear reaction (especially fission and fusion) or nuclear transition.

Nuclear fusion: A nuclear reaction with two light nuclei combining into a heavier nucleus.

Plasma: An electrically neutral gas mixture of particles, electrons, and electrically neutral particles. High-temperature hydrogen plasma can be used as a fuel for controlled fusion experiments.

Radioactive decay: A spontaneous nuclear transformation phenomenon in which a nucleus emits particles or γ-radiation, emits X-rays after capturing orbital electrons or undergoes spontaneous nuclear fission.

Decay constant (disintegration constant): The rate of decay.

Decay energy (Disintegration energy): The energy released by radioactive decay.

Decay scheme: A graphical representation of the decay of a radionuclide detailing nuclear data such as energy level, radiation type, and half-life.

Half-life: The time required for half the activity in a single radioactive decay process.

Radioactive equilibrium: A state in which each radionuclide decays exponentially over time with the same half-life of its precursor in the chain, in other words, each radioactive nuclide decays at the same rate of being produced. The radioactive equilibrium is possibly achieved only when the half-life of the precursor nuclide is longer than those of the daughter nuclides in its later generations in the decay chain. If the half-live of the precursor nuclide is long enough that its change during observation is negligible, the radioactivity of all nuclides in the decaying system is nearly equal to each other. Such a radioactive equilibrium is called the long-term equilibrium. Otherwise, it is called a temporary equilibrium.

Specific activity: The activity per quantity of atoms of a particular radionuclide.

Thermal neutron: A neutron in thermal equilibrium with its surroundings.

Cold neutron: A Neutron with the kinetic energy of the order of milli-electron volts or less.

Epithermal neutron (epithermal neutron): The neutron with kinetic energies above that of thermal perturbation. This term often refers only to neutrons with energies just above the energy range of thermal energy (i.e., comparable to chemical bonding energy).

Ultracold neutron (UCN): A neutron with single-digit velocities in m/s. their kinetic energy is of the order of 10^{-7} eV or ~ 1 mK.

Slow neutron: A neutron with kinetic energy below a specific value, selected depending on application scenarios. For example, this value is typically 1 eV in reactor physics, the effective cadmium cut-off energy (about 0.6 eV) in dosimetry, and 1 keV in neutron nuclear reaction studies.

Fast neutron: A neutron with kinetic energy greater than a specified value, selected depending on application scenarios. The value is typically the boundary of entering the indistinguishable resonance energy region (above 10 keV) in neutron nuclear reaction studies and is usually 0.1 meV in reactor physics.

Resonance neutron: A neutron with kinetic energy in the energy range where the neutron's nuclear reaction cross-section appears to resonate. This energy range is highly variable, usually between 1 eV and 1 keV.

Photoelectric effect (absorption): The phenomenon of atoms absorbing photons and emitting orbital electrons. The absorption of photons and emission of electrons from the surface of certain media is also called the photoelectric effect.

Compton effect: The effect whereby X- or γ-radiations are scattered on a material with an increase in wavelength by matter. Scattering occurs when a photon interacts with free electrons or electrons that can be seen as free electrons. Part of the energy and momentum of the incident photon is transferred to the electron and the rest is carried away by the scattered photon.

Cerenkov radiation: The electromagnetic radiation emitted when a charged particle passes through a dielectric medium at a speed greater than the velocity of ling in that medium.

Neutron diffraction: The diffraction of neutrons incident on a crystal when their wavelength is comparable to the lattice space of the crystal. Neutron diffraction is a crystallographic method used to determine the atomic and/or magnetic structure of materials.

Doppler effect: Changes in the wavelength/frequency of radiation produced by the relative motion between the source and observer.

Spallation: A high-energy nuclear reaction in which a nucleus bombarded by an incident particle with sufficient energy (typically greater than ~ 50 meV) splits into numerous lighter nuclei.

Threshold energy: The minimum value of the kinetic energy of an incident particle (laboratory system) required to trigger a specific nuclear reaction.

Cross-section: The measurement of the likelihood of a given particle interacting with a specific species of incident particle, expressed with the unit of the barn (b, $1\text{b} = 10^{-28}\ \text{m}^2$) in terms of area. It is the quotient of the probability of a specific reaction of each target particle divided by the injection of that incident particle, its value depends on the energy of the bombarding particle and the kind of reaction.

Nuclear fission: The splitting of a heavy atomic nucleus into two (in a few cases, three or more) fragments of the same order of mass, usually concomitant with neutron emission and γ-radiation, and in a few cases, lightly charged particles.

Fission energy: The energy released in the atomic nucleus fission.

Fission fragment: The nuclide with certain kinetic energy produced by the fission of a nucleus.

Fission yield: The fraction of given fission products produced per fission. Fission products with mass numbers around 90 and 140 have high fission yields.

Nuclear chemistry: The branch of chemistry that deals with nuclei and nuclear reactions, using chemical methods or methods with a combination of chemistry and physics. Sometimes, nuclear chemistry refers to the subdiscipline that is concerned with the chemical aspects of nuclear science.

Radiochemistry: The branch of chemistry studying the chemical and physical properties of radioactive elements, utilizing both radioactive and chemical characteristics of elements and compounds to address technical needs in many fields.

Nuclear recoil: The movement of the remaining nucleus conferred by nuclear collisions, nuclear transitions, or radiation action.

Radioactive standard: A radioactive source whose properties and activities are known in a defined period, which can be used as a comparative standard or reference.

Radioactive purity: The ratio, expressed as a percentage, of the radioactivity of the desired radionuclide to the total radioactivity of the source.

Radiochemical purity (RCP): The proportion of the total radioactivity in the sample which is present as the desired radiolabelled species.

Cooling: To weaken the radioactive activity of a substance by radioactive decay.

Decontamination: The process of removing or reducing radioactive contamination by physical, chemical, or biological means from a person, object, or place, which can be divided into initial decontamination, deep decontamination, in-service decontamination, accidental decontamination, and decommissioning decontamination.

Decontamination factor: The ratio of activity before and after decontamination of a radioactively contaminated object. It is used to describe the decontamination efficiency of a decontamination operation, either for a specific radionuclide or for the total radioactive contaminant.

Carrier: Another substance that carries a trace amount of a specific substance in an appropriate quantity and participates in chemical or physical processes.

Ion exchange membrane: A polymer membrane bearing ionic groups with selective permeability to the specific ions in solution.

Isotope effect: The variation of certain physical and chemical characteristics of an element by the mass of the isotopes involved.

Isotopic exchange: The chemical exchange in which two atoms belonging to different isotopes of the same element exchange valency states or locations in the same or different molecules. The isotopic exchange involves the substitution of one isotope of an element by another in the molecules of a given substance without changing their elemental composition.

Isotopic exchange: The chemical reactions in which the reactants and products are chemically identical but have different isotopic compositions. [József Kónya and Noémi M. Nagy. Nuclear and Radiochemistry, 2nd Ed., 2018, Elsevier].

Isotopic equilibrium: An equilibrium state of the distribution of the isotopes achieved in isotope exchange.

Accelerator: A device to elevate the kinetic energy of a charged particle by more than 0.1 meV.

Electron beam (EB): Stream of electrons (e.g. betatron) generated by heat (thermionic emission), the bombardment of charged atoms or particles (secondary electron emission), or strong electric fields (field emission). The high-energy electron beam provided by an accelerator is one of the most important sources of particles and energy for radiation processing and research. It has the advantages of particle beam stability and processing feasibility with reliable and adjustable parameters, while with high initial construction costs, high maintenance costs, and requires specialized knowledge of the operator.

Radiation source: All substances or objects that can cause radiation exposure by electing ionizing radiation or releasing radioactive material. A radioactive source is only one type of radiation source referred to as a source of radiation exposure caused by radioactive materials.

Sealed source: A solid radioactive material sealed in a case or cemented tightly in a cover.

(Orbital) electron capture: The radioactive transformation of a nucleus into another by capturing an orbital electron.

Internal conversion: A nuclear transition competing with γ-radiation to convert the excitation energy of the nucleus directly into that of the shell electrons in that it de-excites the nucleus.

Auger effect: The de-excitation of an atom in an excited state, by releasing orbital electrons instead of X-radiation due to the filling of the inner-shell holes with the outer-shell electrons.

Mossbauer effect: Recoil-free emission and recoil-free resonant absorption of γ-radiation.

1.2.4 Radiation and Rays

The phenomenon of a substance emitting rays is called radiation, including ionizing radiation and non-ionizing radiation. Radiation that causes the ionization of matter is called ionizing radiation. There are many types of ionizing radiation, including electromagnetic radiation such as X-ray and γ-ray, charged particle radiation such as α-ray, β-ray, electron beam, proton ray, deuteron ray, heavy ion beam, meson beam, etc., and uncharged particle radiation, namely neutrons. Ionizing radiation is predominantly produced by nuclear reactors, accelerators, and radioactive sources. Non-ionizing radiation is the radiation that cannot cause the ionization of matter because of its low energy, such as infrared rays, microwaves, etc.

1.2.5 Nuclear Decay and Nuclear Reaction

Nuclear decay, also known as radioactive decay, is a random process by which an unstable nuclide, resulting from the excess or insufficiency of protons or neutrons in the atomic nucleus, spontaneously transforms to another one, concomitant with emitting radiation or particle. Generally, the nucleus before decay is called the parent, while those formed after decay are the daughter. If the daughter nucleus is still radioactive and decays, the daughters of the parent are in turn the 1st generation, the 2nd generation …, and the nth generation daughter nucleus.

The important low of radioactive decay is that the number of radioactive nuclides decreases exponentially with time. When the initial number of the radioactive nuclei is N_0, the number of nuclei that do not undergo radioactive decomposing during time t is:

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

where λ (with the unit of s^{-1}) is the decay constant, meaning the decay probability of a nucleus per unit of time. The value of the decay constant is related to the radionuclide, thus, it is independent of physical and chemical conditions (pressure, temperature, chemical environment, etc.).

Nuclear decay is commonly composed of alpha decay, beta decay, and gamma decay. Additionally, there are other forms of decay, such as spontaneous fission, slow-emitting protons, slow-emitting neutrons, etc.

Alpha decay (or α-decay) represents the disintegration of a parent nucleus to a daughter through the emission of the nucleus of a helium atom (alpha particle). In practice, α-decay has only been observed in nuclides that are considerably heavier than a nickel. The lightest known alpha emitters are the lightest isotopes (mass numbers 106–110) of tellurium (element 52). Alpha particles are commonly emitted by all the heavy radioactive nuclei in nature such as uranium, thorium, or radium, as well as the transuranic elements like neptunium, plutonium, or americium.

Beta-decay (or β-decay) represents the disintegration of a parent nucleus to a daughter through the emission of beta particles. If a nucleus emits a beta particle, it loses an electron (or positron). In this case, the mass number of daughter nuclei remains the same, but the daughter nucleus will form different elements. Beta-decay consists of three forms, namely negative beta decay (β^--decay), positive beta decay

(β^+-decay), and inverse beta decay (orbital electron capture). In β^--decay, a neutron-rich nucleus emits a high-energy electron and an antineutrino, and the nuclear charge increases by one unit to compensate for the negative electric charge. In β^+-decay, a proton-rich nucleus emits a positron (antiparticle of electron with the same mass as electrons but positive electric charge) and a neutrino, and the nuclear charge reduces by one unit. In the orbital electron capture process, a proton-rich nucleus captures an outer electron accompanied by emitting a neutrino, and the nuclear charge reduces by one unit. The negative or positive electron released in beta decay is not inherent but generated by the inter-conversion between proton and neutron within the nucleus. The natural radionuclides mainly occur β^--decay.

Gamma decay (or γ-decay) represents the disintegration (gamma radioactivity) of a parent nucleus (in a high energy state and excited state) to a daughter (in a lower energy state) through the emission of gamma rays (high energy photons). In this case, the daughter nucleus remains the same mass number and nuclear charge number but in a different energy state. Gamma decay typically accompanies other forms of decay, such as α- or β-decay, because radionuclides in excited states are generated in the decay of a parent radionuclide in practice.

A nuclear reaction is a process whereby a nucleus interacts with another nucleus or subatomic particle to produce one or more new particles or gamma rays. Consequently, a nuclear reaction must cause a transformation of at least one nuclide to another. The interaction between two nuclei or subatomic particles without any nucleus changes is called a nuclear scattering, rather than a nuclear reaction. Perhaps the fusion reactions in stars and the Sun are the most notable nuclear reactions. A fusion reaction (or thermonuclear reaction) is a nuclear reaction whereby two or more light nuclei (protium, deuterium, tritium, lithium, etc.) collide at very high energy (supplied by the thermal movement under the condition of a high-temperature and high-density state) and fuse into a new nucleus. Fission reaction is the most notable man-controllable nuclear chain reaction in nuclear reactors. A nuclear chain reaction is a self-propagating sequence of nuclear reactions in which one of the reaction products can cause the same kind of reaction. For example, a nuclear fission chain reaction is a self-propagating sequence of fission reactions in which neutrons released in fission produce additional fission in at least one other nucleus.

1.2.6 Interaction of Alpha Radiation with Matter

An alpha particle emitted by nuclear decay is essentially a helium nucleus with two positive charges, with the energy of typically 4–9 meV. The interaction of alpha particles with matter principally consists of ionization, excitation, scattering, and nuclear reactions.

Ionization and excitation. When passing through matter, alpha particles transfer energy to the atomic shell electrons of their surrounding atoms through Coulomb interactions between the positive charge and the negative charge of the electrons in the atomic shell orbitals. When the electron gains enough energy to overcome the binding of the nucleus, it can break away from the atom and become a free electron, forming ion pairs with positive ions. This phenomenon is known as ionization. If the kinetic energy of free electrons is high enough, they can also cause the ionization of other atoms. We call the former primary ionization and the latter secondary ionization. About 35 eV of energy is required to produce one ion pair in air. An alpha particle of 5 meV can produce about 1.5×10^5 ion pairs in air. An alpha particle passing through matter produces many ion pairs in its track, and the distribution of ion pairs is uneven. The number of ion pairs yielded per unit travel distance of an alpha particle is the specific ionization or ionization density.

If the energy absorbed in Coulomb interactions is inadequate to override the ionization energy, shell electrons cannot become free electrons. In this case, the atom is in an excited state as the absorbed energy raises shell electrons to higher energy levels. This phenomenon is called excitation. The excited atom then returns to the ground state by emitting X-rays bearing specific energy. Additionally, the excited atom can return to the ground state in another way. The excitation energy can be transferred to an orbital electron, which makes the electron gain enough energy to escape and becomes a free electron (i.e., an oscillator). This phenomenon is termed the oscillator effect.

Scattering. The direction of an alpha particle that moves in the matter can be changed by the interactions between the Coulomb force, the electrons outside the nucleus, and the nuclear force from the interaction with the nucleus. Such a phenomenon is termed scatting, including elastic scattering and inelastic scattering. Elastic scattering occurs with no change in the total kinetic energy including the incident alpha particle and the scattered nucleus. Inelastic scattering occurs with the energetic change of the system. Elastic scattering is the principle for the incident alpha particle. For the scattering of alpha particles perpendicularly incident to a scatterer, the small-angle scattering is predominant, and only a little chance of the large-angle scattering occurring. The scattering effect reduces the number of alpha particles traveling along the original direction. However, the loss of alpha particles resulting from scattering is much less than those resulting from ionization and excitation.

Nuclear reactions. Commonly, alpha particles have a rare chance to trigger nuclear reactions. However, when α-particles interact with elements like Be, B, F, Li, Na, and O, the (α, n) reaction occurs and neutrons are released, which is the principal way to prepare isotopic neutron sources.

1.2.7 Interactions of β-Rays with Matter

Beta particles are high-speed electrons (both positive and negative) electing from the nucleus in β-decay. Beta particles (usually with energies less than 4 meV) interact with matter via excitation, ionization, scattering, and secondary radiation.

Excitation and Ionization. As alpha particles do, beta particles can also ionize the atoms/molecules of a substance, and the energy consumption (about 32.5 eV in the air) for a beta particle to produce an ionic pair is almost independent of its velocity. However, the specific ionization value of a beta particle is much less than that of an alpha particle with the same energy. Besides, compared to an alpha particle with the same velocity, a beta particle is also of much lower specific ionization value. For instance, a 5 meV α-particle produces about 3000 ionic pairs of positive and negative charges per micron in water, while a 1 meV β-particle only produces 5 ionic pairs per micron. What we provided here is the average specific ionization value because the β-particle is of a continuous energy spectrum. For monoenergetic fast electrons, the magnitude of the specific ionization value in the air relates to the electronic velocity. The higher the electronic velocity, the smaller the specific ionization value.

Scattering. Because beta particles are much less massive than alpha particles, they are more likely to be scattered. The scattering of beta particles is much more complex than that of alpha particles. Beta particles can be scattered not only by the nucleus but also by orbital electrons. Scattering always occurs multiple times before a beta particle ends its range. The multiple occurrences of large-angle and small-angle scattering will result in backscattering (scattering angles greater than 90°).

Secondary radiation. Scattering in the Coulomb field of orbital electrons and the nuclear force field of a nucleus change the moving direction and speed of beta particles, concomitant with the emission of electromagnetic waves. This process is called bremsstrahlung. Bremsstrahlung has a continuous energy spectrum. Bremsstrahlung occurs with a high probability when beta particles interact with heavy elements.

Besides bremsstrahlung, characteristic X-rays can also be emitted by the interaction between atoms in the matter and fast electrons. Excitation of the target atoms occurs in collisions with Fast-moving electrons. A collision with fast-moving electrons emits an inner-shell electron from the atom, an outer-shell electron then falls into the inner shell to fill the vacancy. In the process, a single photon is emitted by the atom with energy equal to the difference between the inner-shell and outer-shell vacancy states. This energy difference usually corresponds to photon wavelengths in the X-ray region of the spectrum. Additionally, a collision excites the valence electrons of an atom to higher energetic states. When returning to the ground state, they emit visible light and ultraviolet light. These secondary radiations are collectively called fluorescence.

1.2.8 Interaction of Gamma Rays with Matter

Gamma rays are high-energy electromagnetic waves emitted during the nucleus transformations. The wavelength range of gamma rays is 10^{-8}–10^{-11} cm, shorter than that of ultraviolet radiation. Interactions of gamma rays with the matter have a dozen forms, depending on the energy of the incident γ-rays. The neutral γ-rays interact with matter differently from charged particles. As discussed before, charged particles collide with atoms multiple times in their journey, transferring their energy to the environment in a gradual process. However, γ photons transfer most or all of their energy to atoms in a single interaction with the nuclei or extranuclear electrons. The energy of γ-rays emitted from isotopic radioactive sources is generally in the range of a few keV to 2 meV.

For γ-rays produced in radioactive decay or the inner-shell electronic transition, their interactions with matter are principally classified into three types, termed as the photoelectric effect, the Compton-Wuyouxun effect, and the electron pair effect. Other effects, such as Rayleigh scattering, photonuclear reactions, etc., are generally secondary because their reaction cross-sections are much smaller. The electrons newly yield in the interaction of γ-rays with the matter generally have higher energy and can undergo secondary ionization.

Photoelectric effect. A γ-photon undergoes an interaction with an electron that is bound in an atom. In this interaction, the incident photon completely transfers its energy (E_γ) to a bound electron, and the energetic electron (photoelectron) breaks free and emits from its bond shells. This is termed the photoelectric effect. The kinetic energy of the photoelectron is determined by the following equation.

$$E_e = E_\gamma - E_i \tag{1.1}$$

where E_i is the escape work of electrons or named the binding energy of electrons in atomic energy (shell), wherein i represents the electron subshell, i = K, L, ... E_γ is the energy of the incident photon.

In the photoelectric effect, the direction of photoelectron emission is not isotropic concerning the incident direction of γ-photon, depending on the energy of the incident γ-photon (E_γ). When the incident γ-photon is of relatively small energy (20 keV), the photoelectron emission direction is almost vertical to the incident direction γ-photon. With the increase of incident energy, the direction of photoelectron emission gradually tends to be the same as the incident photon. Like ordinary electrons interacting with matter, photoelectrons are also stopped by gradually losing energy through excitation and ionization. The atom also returns to the ground state and emits characteristic X-rays after emitting photoelectrons.

Compton-Wu Youxun Effect. For γ-rays with higher energy, the binding energy of shell electrons can be ignored and regarded as free electrons. The inelastic collision between the incident γ-photons and free electrons deflect the incident gamma photon through an angle (θ) concerning its original direction and decreases its energy (decrease in photon's frequency). This is the Compton-Wu Youxun Effect. In this effect, the electron gains energy $E_\beta = E_\gamma - E_\gamma'$, where E_γ is the energy of the incident proton, and E_γ' is the scattered photon. Besides absorber, the probability of the Compton-Wu Yusen effect depends on the energy of the incident γ-rays E_γ, the higher the E_γ, the lower the occurrence.

Electron–positron pair effect. A gamma-ray with energy greater than twice the electron rest mass (1.022 meV) is annihilated in the nuclear electric field of a nearby atomic nucleus, resulting in the creation of an electron–positron pair. In this process, the gamma-ray converts part of the energy into the rest mass of the electron–positron pair and the others into the kinetic energy of the electron–positron pair. Besides absorber, the probability of producing the electron–positron pair also depends on the energy of the incident γ-particle ($E_\gamma \geq 1.022$ meV), the higher the E_γ, the larger the kinetic energy of the electron–positron pair. The electron is stopped by gradually losing energy through excitation and ionization in interaction with matter, whereas the positron combines with an electron and converts to γ-ray after losing its kinetic energy. This process is called annihilation.

For the three interactions of γ-rays with the matter mentioned above, the Compton-Wu effect and the photoelectric effect are always present simultaneously, and the electron–positron pair effect is also present when $E_\gamma \geq 1.022$ meV.

1.2.9 Interaction of Neutrons with Matter

Neutron, present in all atomic nuclei except hydrogen, is an important component of an atomic nucleus. The mass of neutrons is approximately equal to that of protons. Neutrons are divided into fast neutrons, medium-energy neutrons, and thermal neutrons according to their kinetic energy. Neutrons of kinetic energy greater than 100 keV are commonly named fast neutrons. Neutrons in thermal equilibrium with the surrounding medium are commonly named thermal neutrons or slow neutrons, the most probable energy of thermal neutrons at 20 °C for Maxwellian distribution is 0.025 eV. Neutrons with energy between those for fast and thermal neutrons are named medium-energy neutrons or superthermal neutrons.

Like γ-rays, uncharged neutrons interact with matter in completely different ways from charged particles. Neither the orbital electrons nor the electric field caused by a positively charged nucleus affects a neutron’s flight, it only interacts with a nucleus when it’s in the interaction range of the nucleus (10^{-15} m), or it incident into the nucleus. Four interactions occur between neutrons and matter, including scattering, capture, nuclear reaction, and nuclear fission, of which scattering can be divided into elastic and inelastic scattering. Besides the nature of the nuclear matter, the probability of each interaction aforementioned depends principally on the energy of the incident neutron. For example, neutron capture is prevailing for slow neutrons, elastic scattering is prevailing for medium-energy neutrons and fast neutrons, and inelastic scattering is predominant for the fast neutrons with energy greater than 10 meV.

In addition to elastic scattering, the above interactions between neutrons and matter will lead to secondary radiation. From the viewpoint of radiation protection, secondary radiation caused by neutrons is of considerable importance. What we usually encounter in practice are fast neutrons. For these neutrons, the energy lost in the elastic scattering is greater when they collide with light matters than that with heavy matters. When collides with a hydrogen nucleus, a fast neutron can transfer almost half of its energy to the recoil proton. Therefore, the substances bearing many hydrogen atoms in the structure are good neutron shielding materials. For example, water and paraffin are the most commonly used neutron shielding materials, which are cheap, easily available, and effective.

The probability of the reactions is commonly described as their microscopic cross-sections. The microscopic cross-section represents the effective target area of all the nuclei contained in the volume of the material (such as fuel pellet). The units are given in cm^{-1}. It is the probability of neutron-nucleus interaction per centimeter of neutron travel. All the reactions including elastic scattering, inelastic scattering, radiation capture, nuclear reaction, and nuclear fission have a chance to occur independently. The total microscopic cross-section σ_t expresses the probability of any interaction taking place.

Scattering. Scattering includes elastic and inelastic scattering. Elastic scattering occurs when a target nucleus deflects the incident neutron by an angle and simultaneously recoils. The neutron-neutron interaction system does not lose energy and momentum after elastic scattering. It is to say, elastic scattering cannot excite the target nucleus, and therefore no γ-rays are emitted. The incident neutron distributes its kinetic energy to the recoil nucleus and the scattered neutron. The lighter the target nucleus, the more energy it gains, in other words, the incident neutron loses more energy. The fast neutron loses its kinetic energy through multiple times elastic scattering and becomes a thermal neutron. However, if the incident neutron consumes part of the energy to excite the target nucleus and emits γ-rays when the nucleus returns to the ground state, inelastic scattering occurs. Inelastic scattering is essential only for the scattering of fast neutrons with heavy nuclei.

Radiation capture. Radiation capture is a nuclear reaction in which the incident neutron is completely absorbed, resulting in a compound nucleus. The compound nucleus then decays to its ground state by gamma emission with an energy of a few keV. This capture reaction is also called the (n, γ) reaction. Sometimes, some isotopes have a great chance to capture the neutrons of specific energy in the superthermal region. This phenomenon is called resonance capture or resonance absorption.

(n, α), (n, p), (n, d) reactions. (n, α), (n, p), and (n, d) reactions are the nucleus reactions caused by the collision with neutrons, named after the emitting, charged helium nuclei (α), protons (p), and deuterons (d), respectively. Nuclear reactions emitting charged particles are less common than radiation capture. Charged particles must overcome the Coulombic attraction to escape from the nucleus. Consequently, the reactions with the emission of charged particles are likely to occur in the collision of light nuclei with fast neutrons. But there are exceptions, for instance, the 7Li(n, α) reaction is easy to happen through collision with thermal neutrons.

Nuclear fission. Nuclear fission is a nuclear reaction in which a heavy nucleus interacts with a neutron split into two or more fission fragments (lighter nuclei) and emits one or more neutrons, with the release of a large amount of energy concomitantly. Nuclear fission occurs when ^{233}U, ^{235}U, and ^{239}Pu interact with thermal neutrons and heavy nuclei interact with fast neutrons.

1.2.10 Radioanalytical Technology

Labeling and labeled compound: Labeling is to replace one or more atoms or chemical groups in a compound with easily recognizable atoms or groups. The product is called a labeled compound, and the readily recognizable atoms or groups in a labeled compound are tracer atoms or groups. Labeling with radionuclides as tracers are called radioactive labeling, which produces radioactively labeled substances such as $Na^{18}F$, $^{14}CH_3COOOH$, etc.

Stable nuclide labeled compound: Labeled compound produced by changing the stable isotopic abundance of an element to an observable degree such as $NH_2{}^{13}CH_2COOH$, $^{15}NH_3$, etc.

Non-isotopically labeled compound: Labeled compound obtained by replacing given atoms in its molecule with non-isotopic tracer atoms. For example, selenium-labeled cysteine is produced by replacing the sulfur atom in a cysteine molecule with ^{75}Se.

Multi-labeled compound: The labeled compound introduced two or more tracers to their molecule such as $^{14}CH_3CH(^{15}NH_2)COOH$,$^{14}CH_3CH(NH_2)\,^{13}COOH$, etc.

Specific labeling (S): Label a compound at given positions with the given number of tracer atoms. A specifically labeled compound can be named by providing the name, number, and labeling positions of the tracer atoms before or after the compound name. For example, when alanine is labeled with ^{14}C on methyl (i.e. $^{14}CH_3CH(NH_2)COOH$), it is named S-3-^{14}C-alanine; if ^{14}C is labeled on both methyl and carboxyl (i.e. $^{14}CH_3CH(NH_2)^{14}COOH$), it is named S-1,3-^{14}C-alanine. The symbol S can be omitted when the specific labeling positions are clearly marked out.

Uniform labeling (U): Uniform labeling is to produce a uniform labeled compound in which the ^{14}C-tracer atoms are of uniform distribution in their labeling molecule. In other words, ^{14}C-tracers in a uniform labeled compound are statistically homogeneous for all carbon atoms in the molecule. For example, by labeling a glucose molecule with $^{14}CO_2$ through photosynthesis in plants, the uniform labeled glucose in which ^{14}C-atoms are of uniform distribution in statistics over the six carbons of the glucose molecule can be obtained, which is called U-^{14}C-glucose. In radiopharmaceutical advertising, the symbol UL commonly represents Uniform Labeling.

Nominal location labeling (N or n): Also known as quasi location labeling, refers to that in the labeled compound tracer atoms predicted from the labeling method should be at a specific position, but the identification labeling ratio of tracers at the given position is certainly no more than 95%, depicted with "N" or "n" after the tracer's name. For example, 5-T(n)-uracil indicates that the tritium atom is mainly labeled at the fifth position of the molecule, but more than 5% of the tritium atoms distribute at other positions.

General labeling (G): Refers to that tritium atoms can probably label all hydrogen atoms at any position in a molecule, the degree of labeling varies with the locations of hydrogen atoms. For example, in a tritium-labeled cholesterol molecule prepared by gas exposure, the hydrogen atoms located in the rings, the angular methyl groups, and the side chains of the molecule are more or less labeled by tritium atoms, but the degrees of labeling at different positions are not the same, which can be named G-T-cholesterol.

(Radioactive) Tracing: Refers to a unique technology that adds a radioactive element or compound in the system of interest to indicate the behavior of its internal substances in a specific chemical or biological process by monitoring the changes of radioactive tracers in situ with radioactive detectors.

Isotope dilution analysis (IDA): A highly accurate and precise analytical technique for measuring element concentrations in a wide array of samples in the natural sciences. In IDA, the initial isotopic composition of the sample is altered by the addition of known amounts of one or more isotopic labeled species, the so-called spike. The quantification is only based on the measurement of isotopic ratios of the sample, spike, and sample-spike mixture.

Radiometric analysis: A quantitative analysis technique that determines the mass of a substance by measuring the radioactivity of the component of the substance.

Neutron activation analysis (NAA): An analytical technique for the qualitative and quantitative determination of elements based on the measurement of radiation released by the decay of radioactive nuclei formed by neutron irradiation of the material. The most suitable source of neutrons for such an application is usually a research reactor. The samples that can be analyzed with this method stem from many different fields including medicine, nutrition, biology, chemistry, forensics, the environment, and mining.

Ion beam analysis: An important family of modern analytical techniques involving the use of MeV ion beams for compositional and structural characterization of materials, which combines the advantages of non-destructive and standardless analysis of the surface and near-surface regions (0–2 μm) of solids. IBA is most advantageously applied to analyze problems where information on elemental composition and depth or thickness are needed.

Neutron radiography: A photographic technique that uses a collimated beam of neutrons to generate an image of an object placed in the beam. The image can provide computer-readable data that generates on photographic film or newer electronic devices.

Radiocrystallography: A technique that uses the diffraction of X-rays, electrons, neutrons, etc. by a solid system to perform crystal structure (especially the parameters of the crystal) and the identification of the crystalline material.

Radioactive dating: A technique of dating objects such as rocks and minerals by determining the components of radionuclides (uranium, carbon-14, potassium-40, etc.) or their decay products.

1.2.11 Radiation Processing Technology

Radiation crosslinking: Radiation crosslinking is based on the effect of high-energy beta and gamma rays. When a polymer material absorbs radiation energy, the microscopic molecular linear long chains are broken, and free radicals are formed. The reaction of free radicals with other chains or radicals and the rearrangement of the polymer chains generate T-shaped structures. Consequently, the two-dimensional polymer chains crosslink each other into a three-dimensional "network", improving the mechanical properties, electrical properties, stress cracking resistance, and service life of polymer material. Radiation crosslinking is one of the mainstream techniques for polymer material modification.

Radiation grafting: The substrate material absorbs radiation energy and produces free radicals, which react with unsaturated monomer molecules to graft the monomers onto the substrate. Organic Polymers, inorganics, woods, paper, and other materials that can produce free radicals are the possible substrates and receive specific properties or functions after radiation grafting. Radiation grafting can be conducted in liquid, solid, and gas phases by co-irradiation or pre-irradiation grafting. For example, radiation grafting with monomers like acrylics or acrylates can significantly elevate the appearance, mechanical strength, coloring performance, processing, washing resistance, and wrinkle resistance of silk, while maintaining its natural advantages.

Radiation polymerization: A polymerization reaction initiated by exposure to radiation rather than a chemical initiator. A significant advantage of radiation polymerization is that no chemical initiator residues and fragments are presented in the materials produced with radiation polymerization, which is of significance for biological and pharmaceutical products. The presence of chemical initiator residues may cause allergy in human cells causing inflammation or leading to blood clotting and blockage of capillaries. Another advantage is that radiation polymerization is normally performed under conditions without high temperature and pressure (also called cold polymerization), which avoids complex chemical process equipment and reduces investment.

Radiation decomposition: The decomposition of larger molecules into small molecules caused by incident radiation. This term here refers to the decomposition of polymer molecules. Due to the main chain fracture triggered by free radicals produced by incident radiation, polymer molecules are decomposed into smaller molecules. Radiation decomposition is used not only to obtain products with special properties but also to protect the environment. From the production aspect, Teflon powder is made of polytetrafluoroethylene by radiation decomposition with inks, coatings, and wear-resistant oils added to achieve excellent lubricating performance. As for environmental protection, natural polymers such as cellulose and shells of marine organisms are made into glucose, chitin, and other widely used products through radiation degradation, which can control pollution and create certain economic benefits as well.

Radiation sterilization: Refers to the use of high-energy radiation to destroy the protein molecular structure and genetic material of bacteria or viruses to kill the bacteria. Radiation sterilization is mainly used for the safe, rapid, and effective disinfection of medical devices and materials that cannot be disinfected by high temperature and high pressure. Additionally, killing mold and spoilage bacteria to prolong the fresh-keeping period of food is also a typical use of radiation sterilization.

1.2.12 Basic Knowledge of Radiation Protection

Since radionuclides and/or ionizing radiation are involved in all areas of nuclear technology research and application, knowledge of radiation protection is important for practitioners in nuclear technology and related industries. Radiation protection is an essential branch of atomic energy science and technology, arising from and developing in the development and utilization of ionizing radiation, radioactive substances, and nuclear energy. Radiation protection is a comprehensively fringe discipline that studies the protection of human beings from or less from exposure to the hazards of ionizing radiation. It involves the disciplines of atomic nuclear physics, radiochemistry, radiation dosimetry, nuclear electronics, radiological medicine, radiobiology, radioecology, etc. The essential task of radiation protection is to protect the environment and safeguard the health and safety of practitioners and the public, and their future generations. Specifically, radiation protection aims to prevent non-random biological effects caused by ionizing radiation and to limit the incidence of random biological effects to an acceptable level. The basic principle of radiation protection is to take appropriate measures to reduce the radiation dose under the maximum permissible dose level (also called the safe dose) for the radiation operators and others working around to ensure personal safety.

In practice, the protection principle for external radiation is that under the premise of source strength controlling, radiation protection measures mainly adopt shielding protection, time protection, and distance protection. For internal radiation, the protection principles are enclosed isolation, purification and ventilation, sealing and containment, and waste disposal. For different radiation sources, different materials can be selected to achieve effective shielding protection. High-density metals like lead (Pb), ordinary concrete, and heavy concrete are generally the shielding materials for γ-rays. Substances with a lower atomic number such as Plexiglas and aluminum (Al) are usually the shielding materials for β-rays, which can reduce the transformation portion of β-rays in the shielding materials to tough radiation. For fast neutron shielding, substances with a low atomic number such as boron (B), especially those with more hydrogen atoms such as water and paraffin can be selected. With the development of protection science and technology, and people's awareness of safety and environmental protection, nuclear technology is becoming more and more widely accepted by the public as a relatively safe and environmentally friendly high-tech industry, while gradually penetrating all sectors of the national economy and transforming traditional technology.

1.3 Applications and Developments of Nuclear Technology

Starting in the mid-1940s, nuclear technology and its applications developed rapidly. The crossover and integration of nuclear technology with other disciplines have contributed to the emergence of many frontier disciplines. Many modern scientific and technological achievements are inseparable from the contribution of nuclear technology. Studies of the interaction of radiations and energy particles with matter, together with the physical, chemical, and biological changes resulting from these interactions constitute the main contents of radiation physics, radiation chemistry, and radiation biology. With the application and rapid development of nuclear technology in medicine, medical physics and nuclear medicine have emerged, involving radionuclide preparation, radionuclide labeled compounds, radiation dose, etc.

The penetration of nuclear technology into various regions of the national economy has contributed to many new industries such as radiation processing, non-destructive testing, nuclear medicine diagnostic equipment, radiotherapy equipment, radiopharmaceutical production, etc. In addition to military use, nuclear technology has also been used in various civil fields such as energy security, industrial testing and processing, agriculture, forestry, fishery, medicine and life science, environmental protection and governance, food preservation, and disinfection of goods. The applications of nuclear technology exhibit its essential capabilities: firstly, information acquisition, such as isotope tracing, neutron activation analysis, neutron photography, process monitoring, non-destructive detection, fire warning and alarm, resource detection, human organ imaging, radioactive immunoassay, etc.; secondly, material modification and processing, such as radiation processing, neutron doping, electrostatic elimination, radiation breeding, ion injection, and others; thirdly, decay energy utilization, such as isotope batteries, light sources, and heat sources.

1.3.1 Nuclear Technology in Energy

Nuclear energy is first applied in national defense. The atomic bomb, hydrogen bomb, as well as various reactors and accelerators that provide the supporting technology and materials for nuclear weapon research and manufacture, represent the technological cutting-edge of the application of nuclear technology. The atomic bomb utilizes the wink release of the huge nuclear energy in the fission of ^{235}U or ^{239}Pu, while the hydrogen bomb uses the fission energy produced by the atomic bomb explosion to trigger the fusion of deuterium and tritium to release huge energies. The power of a hydrogen bomb is generally hundreds of times that of an atomic bomb. The military applications of nuclear technology in national defense are out of the scope of this book.

Nuclear technology is also of increasing significance in addressing the energy crisis. Nuclear power is about 20% of globally total electric power, while in France this figure reaches more than 70%. China, India, and other developing countries are stepping up the construction of nuclear energy to provide adequate energy for the growing industrial production. Especially in China, nuclear power plays a significant role in alleviating the outstanding conflicts in energy production, transmission, and usage caused by unbalanced economic development, unreasonable power industry structure, and imperfect layout of energy production enterprises. Nowadays, civil nuclear mainly uses ^{235}U fission energy to generate power. However, the production and development of fission power are facing insurmountable difficulties such as limited global uranium resources (the inferred resources in the < USD 260/kgU cost category in 2019 is 3346400 tU), growing demand and consumption, nearly no spent fuel for reprocessing, and long-term radiation pollution to the environment. Fusion power, which utilizes the nuclear fusion energy of deuterium and tritium, shall be the final way to solve the energy crisis in the future. The huge ^{2}H reserves in the oceans are an inexhaustible supply of civil fusion power, estimated to last 10^9 years.

1.3.2 Nuclear Technology in the Industry

Nuclear technology is commonly used in detection and analysis, radiation processing, and isotope tracing in industrial processes. Various nuclear instrumentations, nuclear microprobes, and large container detection systems are widely used in industries, which obtain non-electrical parameters and other information in industrial processes using the rays emitted by radionuclides as a source of information. For example, various isotope monitoring instruments such as level meters, density meters, thickness meters, nuclear scales, neutron moisture meters, X-fluorescence analyzers, γ-ray flaw detectors, container detectors, and smoke and fire alarms, have been used for monitoring, nondestructive testing, component analysis, and fire detection of the production processes. ^{60}Co (cobalt-60) container CT detection system, neutron imaging detection system, high-energy electron beam sterilization system, and nuclear technology-based explosives detection device are the latest achievements in the application of nuclear technology.

Radiation processing is a material processing technology using ionizing radiation. It is one of the significant application fields of nuclear technology, including radiation-chemical processes, radiation sterilization, and radiation preservation. Radiation processing has made remarkable achievements on industrial scales in cross-linked cables, heat-shrinkable materials, rubber vulcanization, foam plastics, positive temperature coefficient of resistance (PTC) devices, surface curing, green coatings, neutron transmutation doped monocrystalline silicon, medical and health care products, radiation sterilization, food irradiation, and wastewater and waste gas treatment.

Radiation-chemical processes are novel technological processes in which ionizing radiation is used to change the chemical or physical properties of the system. Material irradiation modification is a typical radiation-chemical process that aims to produce materials with special performances and high additional value, whose products are widely used in communication and electronics, electric transportation, petrochemical industry, aerospace, and many other fields. More than 80 countries around the world have carried out research and application of radiation-chemical processes at present. More than 1000 electron accelerators with a total power of about 45 MW, and approximately 250 irradiators bearing ^{60}Co radioactive sources with the intensity of 9.25×10^{18} Bq (9.25 EBq) have been built up for radiation processing.

High-energy radiation is used in radiation sterilization to kill bacteria and viruses. Compared with traditional sterilization by heating and chemical treatment, radiation sterilization has the advantages of low energy consumption, ambient temperature sterilization, thorough sterilization, easy and quick operation, no chemical residue, and no secondary pollution. It has replaced traditional high-temperature steam-sterilization and chemical sterilization and becoming the prevailing sterilization for medical supplies. Radiation sterilization can be applied to sterilizing thousands of species of medical supplies, including metal products and plastic products, as well as Chinese and Western medicines and cosmetics.

Food irradiation is a technology that improves the safety and extends the shelf life of foods by reducing or eliminating microorganisms and insects. Food irradiation kills bacteria without damaging the food or its health benefits. It is a safe and effective food processing technology. The benefits of food irradiation include prevention of foodborne illness, anticorrosive, control of insects, delay of sprouting and ripening, and sterilization. In November 1980, the Food and Agriculture Organization of the United Nations (FAO), the International Atomic Energy Agency (IAEA), and the World Health Organization (WHO) announced in Geneva that food irradiation underwent an overall average dose of 10 kGy wouldn't result in toxicological hazards and issues related to special nutritional or microbiological safety. Food irradiation is used in many countries to reduce food storage consumption, prevent the spread of foodborne diseases, quarantine the import and export of convenience food, and improve the quality of human life. To meet the needs of radiation processing, isotope irradiation devices and high-power irradiation accelerators with their complete sets of equipment, as well as the large-scale industrial online detectors, safety detection equipment for dangerous goods, and radiation therapy equipment that take γ-isotope and accelerator as ray sources have formed an industrial scale.

Ion implantation is a process in which an energetic ion beam is injected into the surface of solid material, resulting in changing surface composition, and thereby changing the properties of the material surface. Ion implantation is an integral part of integrated circuit manufacturing. This technology pioneered in the first half of the twentieth century has become the dominant method of semiconductor doping.

Nowadays, there are more than 3000 ion implanters for integrated circuits worldwide. The radiation modification of silicon rectifier parts (SCR) by a 12 meV electron accelerator has been widely applied. The technology of injecting metal ions into the material surface by metal vapor vacuum arc (MEVVA) to enhance the mechanical strength and friction resistance of the material surface has also been widely used in tool manufacturing, the automotive industry, and the aerospace industry. The N-type high resistance silicon prepared in the nuclear reactor by the neutron transmutation doping (NTD) technology is suitable to produce high-quality high-resistance materials. Ion beam etching (IBE) is a thin-film technology that utilizes an ion source to carry out material removal processes on a substrate. IBE is a type of ion beam sputtering that helps ensure excellent adhesion and precise formation of 3D structures, whether used for pre-clean or patterned etching. IBE offers excellent process control, precision for multilayer stacks, thorough substrate preparation, and high uptime. As an industrial technique, ion implantation exhibits high controllability and accuracy, implanting any element into the target materials without introducing other impurity elements. Ion implantation also has important applications in the field of material synthesis, including nanoparticles (NPs), positive–negative (PN) junctions, and quantum dots.

1.3.3 Nuclear Technology in Agriculture

Nuclear technologies provide competitive and unique solutions to help fight hunger, reduce malnutrition, improve environmental sustainability, and ensure food safety and authenticity. The application of nuclear technology in agriculture embraces the following four main areas: controlling pests/insects, improving animal health, increasing crop production, and improving food processing.

The nuclear-derived sterile insect technique (SIT) is the most proven and common method where nuclear technology has been utilized to control or eliminate insects. SIT can sterilize mass-raised male pests through radiation including γ-rays and X-rays, and release them back into pest-infested areas and mate with wild females without reproducing. This technique reduces reproduction and suppresses or eradicates established insect pests. It can also prevent the proliferation of invasive species—and is much safer for the environment and human health than applying conventional insecticides. This technique provides sustainable, cost-effective, and environmentally-friendly insect control. Over the past 50 years, the Sterile Insect Technique (SIT) has been successfully used to tackle pests that destroy fruit and kill livestock around the world.

Nuclear technology also plays a significant role in ensuring livestock health in various aspects, such as the research and manufacture of the radiation-attenuated vaccines for helminth parasites and protozoan parasites and the radiation-attenuated microbial pathogens, the diagnosis of infectious diseases, and the diagnosis and characterization of parasitic infections and microbial infections by the radiolabeled probes and radioimmunoassay. Radioisotopes are used to trace the paths of food within an animal's digestive system. This process provides insight into where and how quickly the food is broken down into body tissues or milk, allowing for the determination of the nutritional value of food, and therefore ensuring that commercial feeds can meet the needs of each animal.

In terms of increasing crop yield, the role of nuclear technologies can be seen in a couple of areas. Nuclear technology used in crop breeding can develop improved varieties that better adapt to climate change and help vulnerable countries to ensure their food and nutritional security. Seeds can be irradiated with gamma rays, X-rays, ion, or electron beams to initiate genetic changes. This method increases diversity and allows for a wider selection of genetics for breeding techniques. The resulting crop varieties can have higher yield and better quality, drought, heat, or flooding tolerance, better pests and disease resistance, or shorter growth cycles. More importantly, nuclear technology can reduce the usage of fertilizer. Labeling different quantities and types of fertilizers with radioisotopes allows farmers to directly know the nutrient situation of the land because the labeled fertilizers are tracked as they are absorbed into specific areas of the crops.

The preservation of already harvested or produced food is the final focus area that nuclear technology has influenced in the broad field of agriculture. This technique is called food irradiation, beginning in the early 1920s. Food irradiation aims to discontinue the reproductive cycle of bacteria that often causes the spoiling of food. When exposing the food to controlled amounts of ionizing radiation, the DNA bonds of the targeted bacteria can be broken, which allows for longer shelf life and a less likelihood of food-borne diseases developing.

1.3.4 Nuclear Technology in Medicine

Medicine and life sciences are the most active fields in the applications of nuclear technology, including medical diagnostics, therapy, and life science research.

Nuclear medicine diagnostics involves the use of radiation sources (mostly X-rays) and radionuclides, in which radionuclide diagnosis is the most widely used. Radionuclide diagnosis is based on the principle of radioactive tracing, including in vivo imaging and in vitro diagnosis. In vivo imaging is to introduce radiopharmaceuticals into the body, imaging and measuring the global or regional function of an organ with special instruments. Nowadays, in vivo imaging has developed from the sole use of single-photon emission computed tomography (SPECT) or positron emission computed tomography (PET) diagnosis to the fusion imaging technology combining SPECT or PET with magnetic resonance imaging (MRI) or computed tomography (CT). In vitro diagnosis is to micro-analyze the biologically active substances in the patient's body fluids from outside the body, adopting radioimmunoassay (RIA) methods.

Nuclear medicine therapy utilizes ionizing radiation to kill diseased tissue cells, including external radiation therapy and intra-corporeal radiotherapy (also called radioactive source therapy). External radiation therapy is currently one of the three efficient cancer treatments, which can be divided into external long-range irradiation, intra-cavitary post-mounted brachytherapy, interstitial short-range irradiation, and internal interventional irradiation. Gamma rays and high-energy electrons are the most commonly used radiation sources for external radiotherapy. Intra-corporeal radiotherapy is injecting or placing a radiopharmaceutical or radioactive source into the body for treatment. It has been the focus of clinical medicine for many years. Radio-immune targeted therapy, receptor-mediated targeted therapy, radionuclide gene therapy, and radionuclide particle inter-tissue targeted implantation therapy are all indispensable treatments for malignant diseases like tumors. Intra-corporeal radiotherapy can be superior to external irradiation therapy and chemotherapy in some aspects.

Molecular nuclear medicine drives today's nuclear medicine to a new era, it plays an irreplaceable role in researching receptors, genes, antigens, antibodies, enzymes, neurotransmitters, and various bioactive substances. Besides, cardiac nuclear medicine and neurotransmitter nuclear medicine has received more attention from the medical community. In competition with other imaging technologies and therapeutic methods, nuclear medicine imaging is developing from organ perfusion imaging to molecular nuclear medicine functional imaging (e.g. ^{99m}Tc and ^{123}I receptor-ligand imaging), and the integration of various imaging technologies (such as MRI-PET, MRI-SPECT, CT-PET, and CT-SPECT) acquires three-dimensional (or even four-dimensional) imaging with spatial resolution and good temporal resolution. Nowadays, nuclear medicine therapy is evolving from embolization and internal intervention to molecular-specific targeted therapy (e.g. ^{188}Re receptor-ligand therapy).

Nuclear medical devices and equipment have been continuously refined and updated in developed countries and popularized in developing countries. At present, there are about 2000 ^{60}Co (cobalt-60) devices and 6000 accelerators worldwide for the treatment of cancerous tissues deep inside the human body. The continuous popularization and upgrading of advanced diagnostic instruments (such as PET, SPECT, CT, and MRI) and radiotherapy devices (such as the radioactive sources of ^{60}Co, ^{192}Ir, and ^{137}Cs and accelerators), as well as the continuous development of new radioactive diagnostic and therapeutic drugs, offers the strong impetus to the development of nuclear medicine.

The development of specific radioactive receptor drugs for diagnostic and therapeutic imaging has become one of the most dynamic fields today which marks the level of research and application of radiopharmaceuticals in vivo. PET imaging drugs are the main direction of the development of nuclear medicine imaging for a long period of the future. The focus of the research is to take ^{18}F (fluorine-18) as the main object, including ^{11}C (carbon-11),^{13}N (nitrogen-13), ^{15}O (oxygen-15), etc. to explore the new methods and technologies for the automated and rapid synthesis of drugs. Diagnostic and therapeutic radiopharmaceuticals focusing on ^{99}mTc (technetium-99 m) and $^{186、188}$Re (rhenium-186, 188) are still hot research directions in radiopharmaceutical chemistry and the new light will emerge in the research of internal conversion electron (or oxyelectron) nuclides and their radiopharmaceuticals, and new radiopharmaceuticals such as nano-radiopharmaceuticals (radio-nanopharmaceutics). New radiopharmaceuticals such as radio-nanopharmaceutics, magnetically guided drugs, and new therapeutic methods such as boron neutron capture therapy (BNCT), proton therapy, and heavy ion therapy will appear in clinical applications in the near future.

1.3.5 Nuclear Technology in Environmental Protection

Nuclear technology is commonly used to treat the waste, such as purifying coal-fired flue gas with accelerator electron irradiation and treating wastewater and hard-to-degrade organic waste with gamma rays and electron rays. Compare with traditional methods like landfilling, sea casting, and incineration, nuclear technology has significant advantages in the treatment of wastewater and other radioactive biological wastes, the most prominent of which is that it does not cause secondary pollution of the environment. For example, SO_2 and NO_x are the main atmospheric pollutants of coal-fired flue gas emitted from the coal-fired power plants. By irradiating coal-fired flue gas with the electron beam, SO_2 and NO_x react with the oxidation components like H_2O and O_2 and produce H_2SO_4 and HNO_3. H_2SO_4 and HNO_3 react with NH_3 to produce ammonium sulfate and ammonium nitrate by-products, which can be used directly as fertilizer. Such treatment is the only technology that can remove both sulfur and nitrogen pollutants at the same time, it exhibits many advantages including high efficiency, no secondary pollution, no wastewater treatment, and recyclable by-products. More than 20 devices with variable scales of flue gas desulfurization and denitrification are in operation in Japan, the United States, Germany, Russia, Poland, and other countries. Radiation technology in the treatment of atmosphere, wastewater, and sludge are to use the strong penetrating or ionizing effect of gamma rays and electron rays to cause a series of physical, chemical, and biological reactions, destroying the nucleases or proteins of microorganisms to achieve disinfection and sterilization. When using radiation technology to treat industrial organic wastewater, active substances (such as OH group) produced by irradiation can oxidize and decompose organic pollutants in water to reduce pollution levels. The sludge treated with radiation technology still maintains its original nutrients and can be used directly on farmland as fertilizer or made into compost. Radiation technology is of low treatment cost, short cycle time, and good effect on the treatment of municipal wastewater and sludge. Nowadays, more than 40 radiation treatment wastewater plants in the United States are in use, and almost all the indicators of the effluent are better than those of conventional treatment plants.

In the twenty-first century, nuclear technology has new development opportunities in environmental science and environmental monitoring and protection. Nuclear analytical techniques have become an important part of the quality assurance system for environmental monitoring and analysis. Using the unique characteristics of nuclear analytical techniques such as ultra-sensitivity, high accuracy, and adaptability to harsh conditions, real-time and long-distance environmental monitoring systems can be built, which helps to analyze and assess the chemical species of environmental pollutants for environmental effects assessment, and to identify new pollutants for pollution tracing analysis. Moreover, plasma technology has unique technical advantages for waste treatment, such as the decomposition of harmful substances, high-temperature incineration of municipal waste, and the treatment of various wastewater and waste gas. In the chemical industry, acetylene is known as the "mother of organic synthesis industry". The development of hydrogen plasma technology creates the opportunity for the research of coal into acetylene. Coal and hydrogen ions interact at about 3700 K to produce acetylene. But the petroleum-ethylene processing has gradually replaced traditional coal-acetylene processing, which reduces pollution and achieves the comprehensive use of resources.

In addition, nuclear technology is a powerful tool for scientific research, including in the basic sciences, life sciences, and other disciplines. Using a wide range of analytical and experimental research tools provided by isotopes and ionizing radiation, man's vision extends from macro to micro, dynamically observing natural phenomena from molecular, atomic, and nucleus levels.

Based on the ultrasensitive detection of radionuclides which is incomparable to conventional chemical analysis, isotopic tracing technology plays an irreplaceable role in improving the level of technology in scientific research. Isotope tracing technology is currently the only way to explore the structural and pathological changes of in vivo body on the levels from cell to molecule, which is widely adopted in the research on genes, nucleic acids, proteins, and so on to observe the process of circulatory metabolism and disease occurrence, development, prognosis, and evolution, and explore the pathogenesis of diseases and realize a correct diagnosis. Dynamic tracing technology in agriculture uses trace radionuclides with short half-lives, which is applied for the investigation of the effectiveness and mechanism of fertilizers, the decomposition of harmful substances and residue detection, biological nitrogen fixation, for animal husbandry and veterinary research, and water conservation including the inspection and leakage determination in dams and reservoirs.

The application of nuclear technology significantly contributes to national economic construction during the decades of its development. Its ratio of input to output is as high as 1:5–1:10. Reportingly, the isotopic irradiation technology in developed countries contributes about 2–5% of the total income of the national economy.

In 1991, the contribution of non-power applications of radionuclides and radioactive materials to the U.S. economy reached $257 billion, 3.5 times that of nuclear power ($73 billion), accounting for 3.9% of U.S. GDP and creating about 3.7 million jobs. In 1995, the contribution of U.S. isotopic irradiation technology to the U.S. economy grew to $331 billion, 3.67 times that of nuclear power ($90.2 billion), accounting for 4.7% of U.S. GDP, and creating 3.95 million jobs. In 2000, the Japan Isotope Association announced that the economic scale of Japan's isotope irradiation technology was $71.4 billion, 1.18 times that of nuclear power ($60.6 billion) and 1.7% of Japan's GDP. According to the Chinese Society of Isotope and Radiation

Industry, the output value of nuclear technology applications in China was about CNY300 billion in 2018, with an average annual growth rate of about 15%, which far exceeded the growth rate of China's GDP. Therefore, being a sunrise industry, nuclear technology will be more widely used in line with the rapid growth of the world economy and the rapid development of science and technology.

Exercise

1. What is the definition of nuclear technology?
2. What are the main disciplines involved in nuclear technology?
3. Briefly describe the main application fields of nuclear technology and the main directions in various fields.
4. How to understand that "isotope and radiation technology" is the "light industry in the nuclear industry"?

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