Periodic Table of the Universe

Periodic Table of the Universe:

Symphony of Matter

By

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INTRODUCTION

At the core of the physical and biological sciences, amid the perplexing realm of matter, there exists a profound and intricate order, a harmonious symphony of elements that together form the very essence of our world.

It is this remarkable ensemble that we delve into, for it tells the extraordinary tale of the periodic table, a story steeped in scientific revelation, marked by unparalleled innovation, and a testament to the stubborn spirit of human curiosity.

This book provides a succinct journey through the history of the periodic table, unveiling its roots in the creation of chemical elements within stars, tracking their subsequent discovery, systematic arrangement on Earth, and exploring the enthralling realm of man-made elements.

The opening chapter examines the fundamental principles necessary for comprehending the nuclear transformations responsible for the creation of chemical elements. It offers insights into the fundamentals of astrophysics while embarking on a journey to explore the genesis of the very first elements forged in the crucible of primordial nucleosynthesis.

In the second chapter, we explore the complex web of creation within the core of stars. Stellar nucleosynthesis takes center stage during stellar evolution. Within this cosmic crucible, lighter elements fuse together, birthing their heavier counterparts and thus giving rise to the astonishing diversity of chemical elements that enrich the cosmos.

As we venture into chapter three, our journey takes us through the annals of human history, where we tell the remarkable story of discovering the elements right here on Earth. Our ancestors, in their quest for knowledge, were among the first to recognize the elements in the natural world. They unearthed precious metals, harnessed the power of various ores, and intuitively applied the principles of chemistry to their daily lives.

With the ascent of the scientific method, the pace of discovery quickened, and dedicated researchers began an unyielding pursuit to isolate and characterize new elements.

Chapter four pays tribute to one of the pivotal milestones in the annals of scientific history—the discovery of the Periodic Law. Amid the 19th-century scientific revolution, multiple researchers, including Dmitri Mendeleev and Julius Lothar Meyer, independently realized that the properties of elements exhibited periodic patterns when arranged in ascending order of atomic mass.

This groundbreaking revelation not only organized the elements into a cohesive framework but also paved the way for predicting the existence of yet-to-be-discovered elements with startling precision.

Chapter five surveys the forefront of scientific discovery, the journey through the captivating realm of synthetic elements, culminating in the making of oganesson—a testament to human ingenuity and a pinnacle of the periodic table. Oganesson stands as the element with the highest atomic number and atomic mass among all known elements.

These synthetic elements, produced through painstaking efforts in laboratories via intricate nuclear reactions, represent a profound challenge to the boundaries of our understanding of atomic physics. They defy the conventional and inspire scientific inquiry across the globe.

In Chapter Six, we delve into the electron configurations of all 118 known elements. This foundational knowledge enables chemists to organize the periodic table into distinct blocks, each reflecting the underlying structure of electron shells and subshells. Additionally, we explore the intricate electron configurations of ions, providing deeper insights into their behavior. This chapter not only enhances our understanding of atomic structure but also illuminates the principles governing chemical behavior and reactivity

The concluding chapter provides a detailed account of the long format (32-column) of the periodic table, complete with essential information for each element. This standard configuration accommodates the placement of f-block elements between Groups 2 and 3, providing a comprehensive representation of the periodic table's structure.

Throughout the book, we have included references to recent reviews and have consistently highlighted the works of prominent authors who have conducted extensive studies on various facets of the periodic table. These notable scholars, namely Francis Preston Venable, Johannes Willem van Spronsen, Glenn T. Seaborg, Edward Mazurs, John Emsley, Dennis H. Rouvray, Geoff Rayner-Canham, and Eric R. Scerri, have made invaluable contributions that significantly enhanced our comprehension of the periodic table and its profound relevance in scientific research.

CHAPTER 1

PRIMORDIAL NUCLEOSYNTHESIS

1.1 Fundamental ideas about atomic structure

The atomic structure describes the organization, properties, and behavior of the subatomic particles within an atom. Understanding atomic structure is crucial for explaining the behavior of matter at the atomic level.

Elementary particles

At the onset of the Big Bang, the universe was a high-energy, hot, and dense state where matter and energy were closely intertwined. It was filled with a primordial soup of elementary particles.

Elementary particles, also known as fundamental particles, are the building blocks of matter and are considered to be indivisible and without internal structure. These particles are the smallest entities currently known in physics and are categorized into two main types: fermions and bosons.

Fermions

Fermions are particles that follow Fermi-Dirac statistics, which describe their behavior. They obey the Pauli exclusion principle, meaning that no two fermions can occupy the same quantum state simultaneously. Fermions are further divided into two groups:

a. Quarks: Quarks are elementary particles that are the fundamental constituents of protons and neutrons, which make up atomic nuclei. There are six types, or flavors, of quarks: up, down, charm, strange, top, and bottom. Quarks are never found in isolation but are always bound together by the strong nuclear force to form composite particles called hadrons.

b. Leptons: Leptons are another type of fermion that includes particles such as electrons, muons, and taus, as well as their associated neutrinos. Leptons do not experience the strong nuclear force and do not combine to form composite particles. They have distinct properties and interactions.

Bosons

Bosons are particles that follow Bose-Einstein statistics, which describe their behavior. Unlike fermions, multiple bosons can occupy the same quantum state simultaneously. Bosons are responsible for mediating fundamental forces and carrying energy. Some important bosons include:

a. Photons: Photons are particles of light and electromagnetic radiation. They are the carriers of the electromagnetic force and have no mass.

b. W and Z Bosons: The W and Z bosons are responsible for mediating the weak nuclear force, which participates in certain types of radioactive decay and interactions between elementary particles.

c. Gluons: Gluons are the carriers of the strong nuclear force, which binds quarks together within atomic nuclei.

d. Higgs Boson: The Higgs boson is associated with the Higgs field, which gives elementary particles mass. Its discovery in 2012 confirmed the existence of the Higgs mechanism and completed the particle content of the Standard Model.

These elementary particles are studied and classified within the framework of the Standard Model of particle physics, which describes the fundamental particles and their interactions.

After the Big Bang, as the universe expanded and cooled further, the temperature dropped to around a few billion degrees Kelvin, allowing quarks and gluons to combine and form protons and neutrons. This process, called nucleosynthesis, led to the creation of light atomic nuclei, primarily hydrogen and helium.

Around 380,000 years after the Big Bang, the temperature cooled to about 3,000 degrees Kelvin. At this point, electrons could finally combine with atomic nuclei to form neutral atoms through a process called recombination.

1.2 Particle physics

Particle physics, also known as high-energy physics, is a branch of physics that studies the fundamental particles and their interactions. It aims to understand the nature of matter and the fundamental forces that govern the universe at the smallest scales.

Particle physics investigates the fundamental building blocks of matter and their properties. These particles include quarks, leptons, gauge bosons, and the recently discovered Higgs boson. Quarks and leptons are considered elementary particles, meaning they have no internal structure. Quarks combine to form composite particles called hadrons, such as protons and neutrons, while leptons, like electrons and neutrinos, do not participate in strong interactions.

Particle physicists use particle accelerators, such as the Large Hadron Collider (LHC), to collide particles at high energies. By studying the resulting particle collisions, physicists can probe the fundamental forces and particles involved. These experiments provide insights into the behavior, properties, and interactions of particles and help validate or refine the theories that describe them, such as the Standard Model.

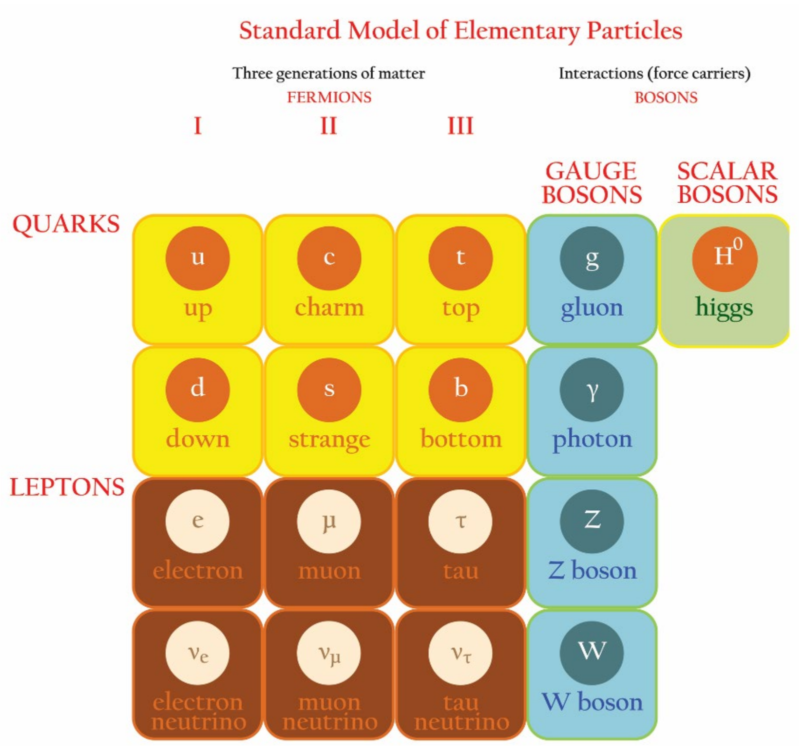

Fig. 1-1 Standard model of elementary particles

Particle physics also addresses fundamental questions about the universe's origin, structure, and evolution. For example, it investigates the asymmetry between matter and antimatter, the existence of dark matter, the nature of neutrinos, and the unification of fundamental forces.

In addition to experimental studies, particle physicists also engage in theoretical research. They develop mathematical models, such as quantum field theory, to describe the behavior of particles and their interactions. These theoretical frameworks provide a deeper understanding of the fundamental laws governing the universe and guide experimental investigations.

1.3 The Standard Model

The Standard Model is a fundamental theory in particle physics that describes the electromagnetic, weak, and strong nuclear forces and the elementary particles that interact through these forces. It provides a framework for understanding the building blocks of matter and their interactions.

The Standard Model incorporates the principles of quantum mechanics and special relativity. It postulates that matter is composed of fundamental particles called quarks and leptons, which are the basic constituents of all matter. There are six types of quarks (up, down, charm, strange, top, and bottom) and six types of leptons (electron, electron neutrino, muon, muon neutrino, tau, and tau neutrino).

The interactions between these particles are mediated by force-carrying particles called gauge bosons. The photon mediates the electromagnetic force, the W and Z bosons mediate the weak nuclear force, and the gluons mediate the strong nuclear force. These forces and particles are collectively referred to as the gauge bosons.

The Higgs boson, which was discovered at the Large Hadron Collider (LHC) in 2012, is also an essential component of the Standard Model. It interacts with other particles and gives them mass. The Higgs field permeates all of space, and particles acquire mass by interacting with this field.

The Standard Model has been extensively evaluated through experiments conducted on particle accelerators, such as the LHC, as well as through precision measurements in other areas of physics. It has been remarkably successful in describing the behavior of elementary particles and their interactions.

1.4 The atom

An atom is the basic unit of matter, consisting of a nucleus at its center and one or more electrons orbiting around the nucleus. It is the fundamental building block of all chemical elements and the smallest particle that retains the chemical properties of an element.

Electrons

Electrons, which are negatively charged, occupy specific energy levels or orbitals around the nucleus. These energy levels are often represented as electron shells. Each shell can hold a specific number of electrons, with the innermost shell being closest to the nucleus and capable of holding the fewest electrons. The arrangement of electrons in an atom determines its chemical properties and how it interacts with other atoms.

Nucleus

The nucleus of an atom contains protons and neutrons. Protons have a positive electrical charge, while neutrons are electrically neutral. The number of protons in the nucleus determines the atom's atomic number and defines its specific element. For example, an atom with one proton is hydrogen, while an atom with six protons is carbon.

Nuclide

A nuclide is a term used in nuclear physics and chemistry to refer to a specific type of atomic nucleus. An atomic nucleus is the central part of an atom that contains protons and neutrons. Each nuclide is uniquely characterized by the number of protons and neutrons it contains.

The notation for a nuclide is usually written as X(A, Z), where

X: Symbol of the chemical element.

A: Mass number.

Z: Atomic number.

For example, the nuclide uranium-235 can be represented as U(235, 92). This means it has 235 total nucleons (protons + neutrons) and 92 protons in its nucleus, therefore X = U, A = 235, and Z = 92.

Nuclides can be stable or unstable (radioactive). Stable nuclides do not undergo spontaneous radioactive decay, while unstable nuclides can decay into other elements through various radioactive processes, emitting particles or radiation in the process.

The nuclide concept (referring to individual nuclear species) emphasizes nuclear properties over chemical properties, while the isotope concept (grouping all atoms of each element) emphasizes chemical over nuclear. The neutron number has large effects on nuclear properties, but its effect on chemical reactions is negligible for most elements.

Isotope:

An isotope is a term used in chemistry and nuclear physics to refer to different forms of an element that have the same number of protons (and thus the same atomic number) but different numbers of neutrons in their atomic nuclei. Since the number of protons determines the chemical properties and identity of an element, isotopes of the same element share similar chemical characteristics.

Isotopes of an element have varying masses due to the different number of neutrons, but they have the same number of protons and electrons, which means their chemical reactions and bonding behavior are essentially the same.

For example, let us take the element carbon (C). Carbon typically has six protons, but it can exist in several isotopes:

C(12, 6)

Carbon-12: It has 6 protons and 6 neutrons, making its mass number 12 (6 protons + 6 neutrons).

C(13, 6)

Carbon-13: It has 6 protons and 7 neutrons, making its mass number 13 (6 protons + 7 neutrons).

C(14, 6)

Carbon-14: It has 6 protons and 8 neutrons, making its mass number 14 (6 protons + 8 neutrons).

All three isotopes are chemically carbon and exhibit similar chemical behavior in most situations. However, they have slightly different masses due to the variation in the number of neutrons.

Chart of nuclides:

A chart of nuclides, also known as a nuclear chart or nuclide chart, is a graphical representation of all known nuclides, displaying them in a table format based on their number of protons (Z) and number of neutrons (N). Each cell in the chart represents a specific nuclide, and the chart provides valuable information about their properties, such as mass number (A), natural abundance, and whether they are stable or radioactive.

It is a two-dimensional graph of isotopes of the elements, in which one axis represents the number of neutrons (symbol N) and the other represents the number of protons (atomic number, symbol Z) in the atomic nucleus.

Since there are thousands of known nuclides, the complete chart can be quite extensive and challenging to represent in its entirety.

1.5 Nuclear physics

Nuclear physics is a branch of physics that focuses on the study of atomic nuclei and their interactions. It deals with the properties, structure, behavior, and transformations of atomic nuclei.

The nucleus, composed of protons and neutrons, is the central core of an atom. Protons carry a positive electric charge, while neutrons have no electric charge. The number of protons determines the element's identity, while the total number of protons and neutrons determines the mass of the nucleus.

1.5.1 Differences between chemistry and nuclear physics

Chemistry and nuclear physics are two distinct scientific disciplines that focus on distinct aspects of matter and energy. While they share some similarities, they differ in terms of their scope, scale, and fundamental principles.

Chemistry is the scientific study of matter, its properties, composition, and interactions. It explores the behavior of atoms and molecules, their bonding, and the transformations they undergo during chemical reactions. Chemistry encompasses a wide range of topics, including organic chemistry, inorganic chemistry, physical chemistry, analytical chemistry, and biochemistry. It investigates the structures and properties of substances, the mechanisms of reactions, and the principles governing chemical phenomena.

On the other hand, nuclear physics is a branch of physics that studies the behavior, structure, and properties of atomic nuclei and the interactions involving subatomic particles within them. It focuses on the nucleus, which contains protons and neutrons, and investigates processes such as nuclear decay, nuclear reactions, and nuclear fusion and fission. Nuclear physics explores the fundamental forces and particles that govern the behavior of atomic nuclei, and it has applications in various fields, including energy production, nuclear medicine, and astrophysics.

Some fundamental differences between chemistry and nuclear physics are:

Scale

Chemistry primarily deals with the behavior of atoms and molecules, which are on the scale of angstroms (10^{-10} meters). Nuclear physics, on the other hand, investigates the behavior of atomic nuclei, which are much smaller than atoms, on the scale of femtometers (10^{-15} meters).

Focus

Chemistry emphasizes the understanding of chemical reactions, bonding, and the properties of different substances. It investigates the behavior of electrons, their arrangement in atoms, and how they interact to form chemical bonds. Nuclear physics focuses on the study of atomic nuclei, their stability, decay modes, and the forces that hold the nucleus together.

Energy and processes

Chemistry generally deals with energy changes associated with chemical reactions, such as the breaking and formation of bonds. Nuclear physics deals with much higher energy processes, including nuclear reactions and transformations that involve the release or absorption of substantial amounts of energy from the nucleus.

Chemical reactions involve relatively small energy changes compared to nuclear reactions. The energy changes in chemical reactions are typically in the form of heat or light.

Nuclear reactions involve much larger energy changes, often in the form of radiation, such as gamma rays or high-energy particles. Nuclear reactions can release vast amounts of energy, as seen in nuclear power plants or nuclear weapons.

Note:

Nuclear chemistry is a sub-discipline of chemistry that involves the chemical reactions of unstable and radioactive elements where both electronic and nuclear changes can occur.

1.5.2 Differences between chemical and nuclear equations

Chemical equations and nuclear equations are two types of equations used to represent distinct types of reactions—chemical reactions and nuclear reactions.

Chemical equations describe reactions involving the rearrangement of atoms and the formation or breaking of chemical bonds, while nuclear equations describe reactions involving changes in the atomic nucleus, such as radioactive decay or nuclear fission/fusion.

The key differences between the two are:

Nature of reactions

Chemical *equations*: represent chemical *reactions*, which involve the rearrangement of atoms and the formation or breaking of chemical bonds. In a chemical reaction, the identity of the elements remains the same, but their arrangement and bonding change.

Nuclear *equations*: represent nuclear *reactions*, which involve changes in the nucleus of an atom, usually producing a different element.

These reactions typically involve the emission or absorption of particles, such as protons, neutrons, or alpha particles, from the nucleus.

Particle interactions

Chemical equations: in chemical reactions, atoms or molecules interact through the sharing or transfer of electrons. Chemical bonds are formed or broken between atoms to create new substances.

Nuclear equations: nuclear reactions involve interactions at the level of the atomic nucleus. These reactions typically involve changes in the number of protons and neutrons in the nucleus, leading to the formation of different isotopes or the conversion of one element into another.

Mass and atomic number

Chemical equations: in chemical reactions, the total mass and atomic number of the reactants and products remain the same. The law of conservation of mass and the law of conservation of atomic number hold true in chemical reactions.

Nuclear equations: in nuclear reactions, the total mass and atomic number may differ between the reactants and products. Nuclear reactions involve changes in the number of protons and neutrons, leading to variations in atomic number and mass.

Examples:

Chemical equations:

A typical example of a chemical equation is the combustion of methane (CH_4) in the presence of oxygen (O_2) to produce carbon dioxide (CO_2) and water (H_2O).

$$\boxed{CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O}$$

Methane burns in the presence of oxygen to produce carbon dioxide and water, as shown in the equation above.

Another example is the formation of iron(III) oxide through the combination of elemental iron (Fe) and molecular oxygen (O_2). See figure 1-2.

The equation can be balanced as follows:

$$4Fe + 3O_2 \rightarrow 2Fe_2O_3$$

The above is a skeletal equation; in reality the reaction occurs in two phases:

$$4Fe + 3O_2 + 2H_2O \rightarrow 4FeO(OH)$$

$$2FeO(OH) \rightarrow Fe_2O_3 + H_2O$$

This process involves using metallic iron as the anode in an electrolytic cell, where it reacts to form iron hydroxide. The resulting iron hydrated iron(III) oxide can then be dehydrated to produce iron(III) oxide.

Nuclear equations:

An example of nuclear equation is the radioactive decay of uranium-238 into thorium-234 and an alpha particle. See figure 2-2.

Uranium-238 (U-238) contains 92 protons and 146 neutrons (238 - 92 = 146). If it undergoes alpha decay, losing 2 protons and 2 neutrons, it will then have 90 protons and 144 neutrons.

The element with 90 protons is thorium (Th), giving it a new mass number of 234 (90 + 144). As a result, the decay process produces thorium-234 and releases an alpha particle:

$${}^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He^{2+}$$

See figure 1-3.

Another example of nuclear equation is the collision of lithium-6 and a deuterium nucleus, resulting in the formation of two alpha particles.

$${}^{6}_{3}Li \rightarrow {}^{2}_{1}H + 2\,{}^{4}_{2}He^{2+}$$

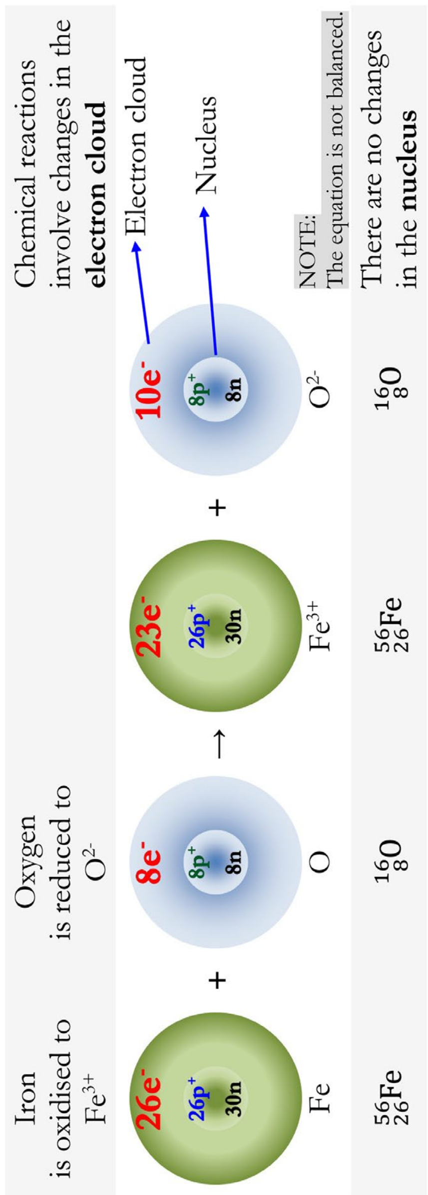

Fig. 1-2 Example of a chemical reaction.

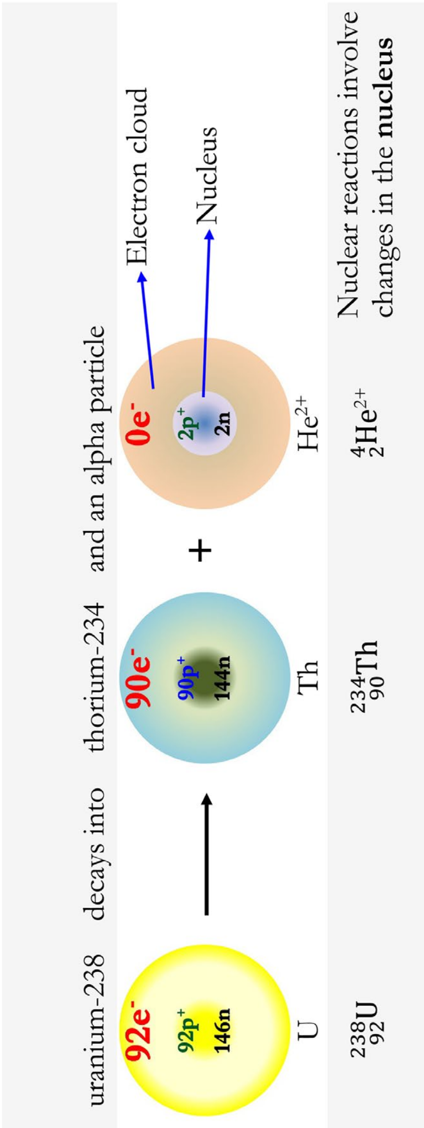

Fig. 1-3 Example of a nuclear reaction.

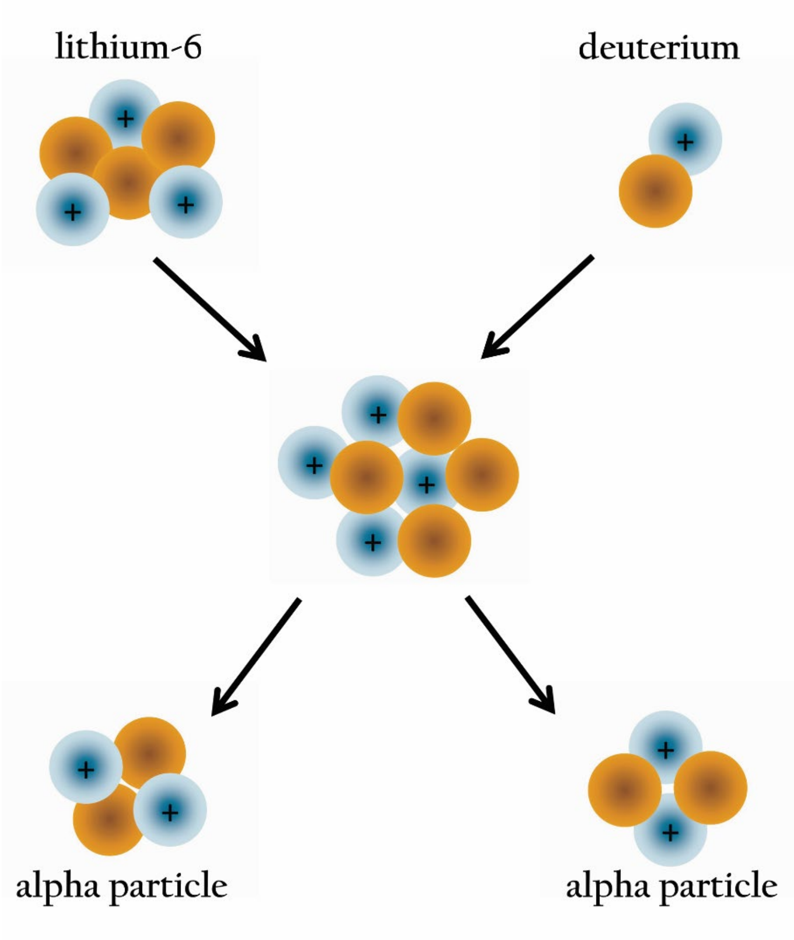

Fig. 1-4 Collision of lithium-6 and a deuterium nucleus.

Some examples of nuclear equations are:

Alpha-bombardment of nitrogen to produce hydrogen and oxygen:

$$^{14}_{7}N + ^{4}_{2}He^{2+} \rightarrow ^{1}_{1}H + ^{17}_{8}O$$

Radioactive decay of thorium-230 into radium-226 and an alpha particle:

$$^{230}_{90}\mathrm{Th} \rightarrow {}^{226}_{88}\mathrm{Ra} + {}^{4}_{2}\mathrm{He}^{2+}$$

Plutonium-239 decay by alpha particle emission:

$$^{239}_{94}\mathrm{Pu} \rightarrow {}^{235}_{92}\mathrm{U} + {}^{4}_{2}\mathrm{He}^{2+}$$

1.6 Radioactive decay

In nuclear physics, "decay" refers to the process by which an unstable atomic nucleus transforms into a more stable configuration by releasing particles or energy. Radioactive decay is a fundamental property of certain isotopes, which are variants of an element with the same number of protons but different numbers of neutrons in their nuclei. These unstable isotopes, also known as radionuclides, undergo radioactive decay to reach a more stable state.

There are several types of radioactive decay:

Alpha decay: The emission of an alpha particle from the nucleus, reducing the atomic number by 2 and the mass number by 4.

Beta decay: The emission of either a beta-minus (β-) particle (an electron) or a beta-plus (β+) particle (a positron) from the nucleus, resulting in a change in the atomic number while the mass number remains the same.

Gamma decay: The emission of gamma rays, high-energy electromagnetic radiation, to release excess energy from an excited nucleus without changing its atomic or mass number.

Other decay modes: Some isotopes may undergo other decay modes, such as neutron emission, proton emission, or electron capture.

The concept of decay is essential in nuclear physics and plays a crucial role in understanding the behavior of atomic nuclei, the stability of isotopes, and the production of various particles in nuclear reactions.

1.6.1 Alpha decay

Alpha decay is a type of radioactive decay in which an atomic nucleus emits an alpha particle. An alpha particle is a type of ionizing radiation composed of two protons and two neutrons, making it identical to a helium-4 nucleus. When an unstable atomic nucleus undergoes alpha decay, it loses two protons and two neutrons, resulting in the transformation of the original parent nucleus into a new daughter nucleus with an atomic number that is reduced by 2 and an atomic mass that is reduced by 4.

The process of alpha decay can be represented by the following generic equation:

Parent nucleus → Daughter nucleus + Alpha particle

For example, a common alpha decay occurs in the decay chain of uranium-238:

$$^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}$$

In this example, a uranium-238 nucleus emits an alpha particle, resulting in the formation of a thorium-234 nucleus as the daughter product, and an alpha particle (helium-4) is released.

Alpha decay is significant because it plays a crucial role in the natural decay of heavy and unstable elements, leading to the formation of more stable isotopes over time.

1.6.2 Beta decay

Beta decay is another type of radioactive decay that occurs in certain unstable atomic nuclei. During beta decay, a nucleus emits either a beta-minus (β^-) particle or a beta-plus (β^+) particle, transforming into a new nucleus with a different atomic number. The emitted beta particle is either an electron (β^-) or a positron (β^+), and the process is accompanied by the conversion of a neutron or a proton within the nucleus.

There are two main types of beta decay:

Beta-minus (β^-) decay: In beta-minus decay, a neutron in the nucleus is transformed into a proton, and an electron (β^-) and an antineutrino are emitted. The antineutrino is a nearly massless and chargeless particle that carries away some of the energy from the decay process. The result is

an increase in the atomic number by one while the mass number remains unchanged.
Example of beta-minus decay:

$$^{14}C \rightarrow {}^{14}N + \beta^- + \nu$$

In this example, a carbon-14 nucleus undergoes beta-minus decay, transforming into a nitrogen-14 nucleus by emitting an electron and an antineutrino.

Beta-plus (β^+) decay: In beta-plus decay, a proton in the nucleus is transformed into a neutron, and a positron (β^+) and a neutrino are emitted. The neutrino is also a nearly massless and chargeless particle, carrying away some of the decay energy. The result is a decrease in the atomic number by one while the mass number remains unchanged.
Example of beta-plus decay:

$$^{22}Na \rightarrow {}^{22}Ne + \beta^+ + \nu$$

In this example, a sodium-22 nucleus undergoes beta-plus decay, transforming into a neon-22 nucleus by emitting a positron and a neutrino.

Both types of beta decay are governed by the weak nuclear force, one of the four fundamental forces of nature. Beta decay is essential for the stability of certain isotopes, as it allows them to transform into more stable configurations over time

1.6.3 Gamma decay

Gamma decay, also known as gamma radiation or gamma emission, is a type of radioactive decay that involves the release of gamma rays from an unstable atomic nucleus. Unlike alpha and beta decay, which involve the emission of particles (alpha particles or beta particles), gamma decay does not result in the formation of new elements or isotopes. Instead, it involves the emission of high-energy electromagnetic waves called gamma rays.

Gamma rays are a form of electromagnetic radiation, similar to X-rays and visible light, but with much higher energy. They have no mass and no electric charge, and they can travel at the speed of light. Gamma rays are extremely penetrating and can pass through various materials, including metals and living tissues, making them potentially hazardous to human health in high doses.

Gamma decay typically follows other types of radioactive decay (e.g., alpha or beta decay). After an atomic nucleus undergoes alpha or beta decay, it may be left in an excited state, which means its energy is higher than its ground state. To reach a more stable and lower-energy state, the nucleus releases the excess energy in the form of gamma rays.

The process of gamma decay is represented by the following generic equation:

Excited nucleus → Ground state nucleus + Gamma ray

For example, in the decay of technetium-99m (^{99m}Tc) used in medical imaging:

$$^{99m}Tc \rightarrow {}^{99}Tc + \gamma$$

Technetium-99m (Tc-99m) → Technetium-99 (Tc-99) + Gamma ray (γ)

In this example, an excited technetium-99m nucleus in a metastable state (^{99m}Tc) emits a gamma ray (γ) to transition to its ground state, which is a more stable configuration.

Note: A metastable nuclear isomer, also known as an isomeric state or nuclear isomer, refers to a specific excited state of an atomic nucleus that has a relatively long half-life compared to other excited states of the same nucleus. This means that the nucleus remains in this excited state for a significant amount of time before it decays to a lower-energy state or ground state through a radioactive decay process.

In simple terms, atomic nuclei can exist in various energy levels or excited states, just like electrons in an atom. However, most of these excited states decay rapidly and emit gamma rays or other particles to transition to a more stable state. In the case of metastable nuclear isomers, the excited state has a longer lifetime due to certain selection rules or conservation laws that make the transition to the ground state less probable or energetically disfavored.

Technetium-99m (^{99m}Tc) is a metastable nuclear isomer of technetium-99 (itself an isotope of technetium), symbolized as ^{99m}Tc.

The term “metastable” indicates that the nuclear isomer is in a state of long-term stability compared to other excited states, but it is not entirely stable since it will eventually undergo decay.

1.7 Nuclear reactions

A nuclear reaction refers to a process in which the structure or composition of atomic nuclei is altered, resulting in the release or absorption of significant amounts of energy. These reactions typically involve the interaction between atomic nuclei, and they can lead to the transformation of one element into another or the splitting of heavy atomic nuclei into lighter ones. There are diverse types of nuclear reactions:

1.7.1 Nuclear fission

Nuclear fission is a nuclear reaction in which the nucleus of an atom, typically a heavy and unstable nucleus like uranium-235 or plutonium-239, is split into two smaller nuclei, along with the release of a large amount of energy. This process is usually initiated by the absorption of a neutron by the nucleus, causing it to become overly excited and unstable.

Examples of nuclear fission reactions include:

Uranium-235 fission: One of the most well-known examples of nuclear fission is the reaction involving uranium-235. When a U-235 nucleus absorbs a slow-moving neutron, it becomes highly unstable and splits into two smaller nuclei, such as xenon-140 and strontium-94, along with the release of several neutrons and a significant amount of energy.

U-235 + neutron → Xe-140 + Sr-94 + 2 neutrons + energy

$$\boxed{{}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{140}_{54}\mathrm{Xe} + {}^{94}_{38}\mathrm{Sr} + 2\,{}^{1}_{0}\mathrm{n} + \mathrm{MeV}}$$

Plutonium-239 fission: Plutonium-239 is another fissile isotope that can undergo nuclear fission. When Pu-239 absorbs a neutron, it splits into two or more smaller fragments, such as xenon-134 and zirconium-103, releasing energy and additional neutrons that can continue the chain reaction.

Pu-239 + neutron → Xe-134 + Zr-103+ 3 neutrons + energy

$$\boxed{{}^{239}_{94}\mathrm{Pu} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{134}_{54}\mathrm{Xe} + {}^{103}_{40}\mathrm{Zr} + 3\,{}^{1}_{0}\mathrm{n} + \mathrm{MeV}}$$

One of the many known fission reactions of uranium-235 induced by absorbing a neutron results in two extremely unstable fission fragments, a barium and a krypton nucleus. These fragments almost instantaneously release three neutrons between themselves, becoming barium-144 and krypton-89.

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{236}_{92}U^* \rightarrow ^{144}_{56}Ba + ^{89}_{36}Kr + 3\,^{1}_{0}n$$

The superscript asterisk means that the nucleus is not in its ground state but in an excited one.

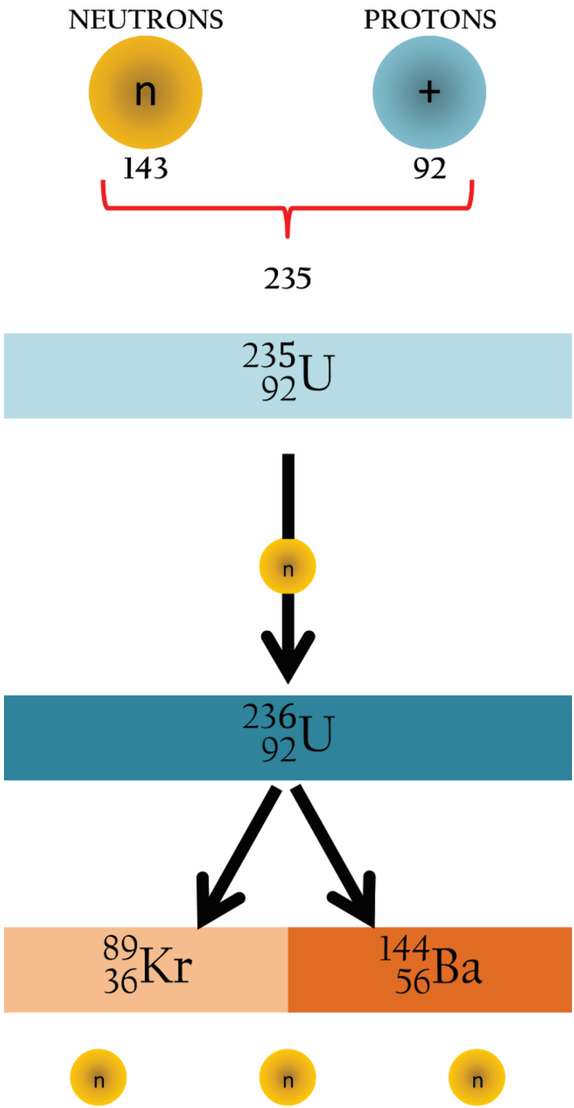

Fig. 1-5 Fission of uranium-235 into krypton-89 and barium-144.