Chapter 6 Nuclear Reactions

Learning objectives

1) familiar with atomic structure and isotope

2) understanding radioactivity, half-life and types of decay

3)Mass-energy equation, mass loss and fusion and fission

Related Vocabularies:

Atomic number; isotope; half-life, radioactivity, alpha decay, beta decay and gamma decay, mass loss.

6.1 History of Nuclear Science

In terms of material structure, the greatest achievement of chemistry in the 19th century was the establishment of the atomic-molecule theory. Chemists inherited the term atom (originally meaning "indivisible") from the ancient Greek atomists. In fact, the understanding atoms that are "indivisible" is extremely valuable. In spite of a heavy price for it, people are still exploring: Are atoms with a diameter of about 10^-8cm really indivisible? Until the end of the 19th century, physicists made three major discoveries in three consecutive years, revealing that atoms still have internal structures, and people began to enter the field of research into the microscopic world smaller than atoms. Three major breakthroughs about the microstructure of matter were made in three consecutive years: in 1895, German physicist Röntgen discovered X-rays; in 1896, French physicist Becquerel discovered radioactivity; in 1897, British physicist J.J. Thomson discovered the electron. These three major discoveries had opened the door to the microscopic world. For more than a century, mankind has explored and understood enormously about the microscopic world, and has attained brilliant achievements.

Before the discovery of X-rays, scientists had been operating cathode ray tubes in laboratories for more than 30 years. Some people also found that the photographic film near the cathode ray tube turned black or had blurry shadows, indicating that X-rays had already been produced. But this phenomenon had not been taken seriously. The observant German physicist W.C. Ròntgen (1845-1923) was doing a gas discharge experiment in a cathode ray tube on the evening of November 8, 1895. In order to avoid the influence of visible light, he used black paper to wrap the discharge tube for observation. Roentgen discovered that a fluorescent screen (coated with fluorescent material platinum barium cyanide) that was a certain distance away from the discharge tube emitted weak fluorescence. He put the fluorescent screen farther away and turned the side coated with fluorescent material away, and still saw the fluorescent screen emitting fluorescence. He was acuminous knowing that this was definitely not caused by cathode rays, but an unknown ray acting on the fluorescent screen. Of course, Roentgen had not yet figured out the nature of this ray at the time, so he named this newly discovered ray X-rays, for which Roentgen won the first Nobel Prize in Physics in history in December 1901.

Figure 6.1, the first X-ray image--- the image of a hand of Ròntgen's wife, adapted from https://www.independent.co.uk/news/science/the-first-xray-photograph-rhodri-marsden-s-interesting-objects-no-86-a6721131.html

Roentgen discovered X-rays, but its source was still a mystery. Many scientists were looking for fluorescent substances for in-depth research. French physicist H. Becquerel (1852-1908) designed an experiment in which that a piece of uranium compound - potassium uranyl sulfate crystal (fluorescent substance) was placed on a photographic film which was wrapped in black paper, and then exposed to the sun. As a result, an image with the same shape as the fluorescent material was found on the film. He thought that it must be the fact that when uranium compounds emit fluorescence when excited by sunlight, and also emit X-rays. Because X-rays have strong penetrating properties, they make the film sensitive to light. However, when he continued his experiments, Paris was cloudy for days and could not get sunlight, so he had to put the uranium salt tightly wrapped in black paper in a drawer. His practical experience inspired him suddenly: If the uranium salt is not exposed to sunlight, will the salt be still sensitive to light? After the film was developed, clear black shadows appeared on it. The results of many experiments have confirmed that the uranium compound itself also emits a ray invisible to the naked eye, which has nothing to do with fluorescence. When he experimented with zinc sulfide and calcium sulfide, he saw nothing. Becquerel finally discovered another the inner secrets of matter—the radioactivity of matter.

The discovery of electrons was linked to the experimental research on cathode rays, and the discovery and research of cathode rays began with the discharging phenomenon of vacuum tube. As early as 1858, the German physicist Julius Plücker discovered cathode rays while using a discharge tube to study gas discharge. What exactly are cathode rays? In the last 30 years of the 19th century, many physicists looked into cathode rays. British physicist William Crookes and others had already proposed that cathode rays are negatively charged particles in terms of that cathode rays are deflected in a magnetic field. Based on the deflection, they calculated that the ratio of charge to mass ($\frac{q}{m}$) of cathode ray particles is 1,000 times larger than that of hydrogen ions. J.J. Thomson designed a new cathode ray tube and used the most advanced vacuum technology at the time to obtain high vacuum. Finally, the cathode rays were stably deflected in the electric field. The deflection direction clearly showed that the cathode rays were made of negatively charged particles. Then he added a magnetic field outside the tube that was perpendicular to both the ray direction and the electric field direction (this magnetic field was generated by the coil outside the tube). When the electric field force (eE) on the particle is equal to the Lorentz force (evB) of the magnetic field, the rays can be prevented from deflecting and hit the center of the tube wall. After calculation, it can be seen that the ratio of charge to mass ($\frac{q}{m}$) of the particles that make up the cathode ray is $\approx 1\times 10^{11} C\cdot kg^{-1}$. Through further experiments, Thomson found that using different materials or changing the type of gas in the tube, the ratio of charge to mass ($\frac{q}{m}$) of the ray particles can be measured which is unchanged, suggesting that this particle is a universal component in various materials. In 1897, Thomson pointed out that cathode rays are composed of negatively charged particles with high speed. This particle was later called an electron.

Electrons were the first microscopic particles discovered. The discovery of electrons plays an extremely important role in the understanding of atoms, because it is a universal component in all substances, contradicting the traditional concept that atoms cannot be divided anymore. The discovery of electrons marked an epoch for mankind's understanding of the microstructure of matter. Thomson not only won the 1906 Nobel Prize in Physics for his discovery of the electron, but also was honored as "the greatest man who first opened the door to elementary particle physics."

6.2 Models of microstructure of Atoms

After British chemist and physicist J. John Dalton (1766-1844) developed the atomic theory, many people believed that the atom was like an extremely tiny solid ball and could not be divided further. After Thomson discovered electrons, people immediately thought that neutral atoms were probably composed of negatively charged electrons and positively charged parts, and the positive and negative charges were equal. So how are they distributed inside the atom?

A. Nucleus-free atom model

In the early 20th century, scientists proposed many ideas, among which Thomson's "nucleus-free atom model" (also known as the "raisin cake model") was the most popular one. He assumed that the positive charges of atoms were evenly distributed throughout the atomic sphere, and electrons were embedded among those positive charges. However, this model was proved incorrect by subsequent experiments.

From 1909 to 1911, British physicist Rutherford (1871-1937) and his collaborators conducted experiments in which alpha particles bombarded gold foil. From a large amount of observation records, they found that the vast majority of α particles still penetrated the gold foil moving forward in the original direction, while only a small number of α particles underwent large deflections. Some of the deflection angle exceeded 90° for a very small amount of α particles, and some even got bounced back (the probability of α particles being reflected back was about one out of 8,000). The large-angle scattering phenomenon of alpha particles in the experiment surprised Rutherford because that requires a large repulsion unless most of the mass and positive charge of the atom are concentrated on a very small nucleus. Based on alpha particle scattering experiments, Rutherford proposed the nuclear structure theory in 1911.

Although Rutherford's nuclear model of the atom was very successful, it had serious deficiencies. For example, electrons rotating around the nucleus have acceleration. According to Maxwell's electromagnetic theory, any charged particle will radiate energy by emitting electromagnetic waves during its accelerated motion. The radius of the electrons orbiting the nucleus will become smaller and smaller, and finally falls on the nucleus, so the atom is unstable. But in fact, atoms are stable. In addition, when electrons rotate around the nucleus, the frequency of electromagnetic waves radiated is equal to the frequency of electrons moving around the nucleus. Atoms will continuously radiate energy. As the energy gradually decreases, the frequency also gradually changes, so the spectrum emitted by atoms should be a continuous spectrum. In fact, the atomic spectrum is a linear spectrum composed of discontinuous thin lines.

B. Bohr Model

The young Danish physicist N. Bohr (1885-1962) firmly believed the model of his teacher Rutherford and tried to propose fundamental corrections. Inspired by the quantization concepts of Planck and Einstein and the experimental formulas of Balmer and Rydberg, Bohr proposed the Bohr model in 1913. After two years of persisiting efforts, applying the quantization concept to to Rutherford's atomic model, and related atomic structure to spectra, Bohr successfully described the structure of hydrogen atoms as shown in Figure 6.2.

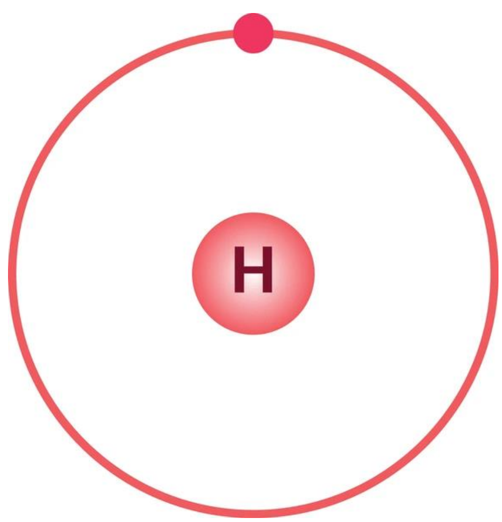

Figure 6.2 Bohr model of atomic structure, adapted from https://www.britannica.com/science/Bohr-model

Bohr successfully described the structure of hydrogen atoms using the quantization concepts of Planck and Einstein, uncovering the puzzling mystery of the hydrogen spectrum which lasted 30 years, significantly contributing to quantum theory and atomic physics. He won the Nobel Prize in Physics in 1922.

While the Bohr model was successful, it also encountered some insurmountable difficulties. Although this theory successfully explains the spectra of hydrogen atoms and hydrogen-like atoms with one extranuclear electron (the extranuclear electron is pulled to one electron ion, such as primary ionized helium ions and secondary ionized lithium ions). But it could not explain the spectrum of the helium atom, which only has one more extranuclear electron than that of the hydrogen atom. Even for the hydrogen atom, there was no way to explain the intensity of its spectral lines based upon the Bohr model. The crux was that Bohr still regarded electrons as particles in classical mechanics; It made a circular motion around the nucleus under the action of electrostatic gravity (centripetal force) with an assumption that no electromagnetic radiation is produced, which is obviously contradictory. Therefore, Bohr's theory is only a semi-classical and semi-quantum theory.

C. **The Atom model in Quantum Mechanics**

A series of difficulties that Bohr’s theory faced to interpret a lot of phenomena had ushered a greater revolution in physics, leading to the establishment and development of quantum mechanics. From 1925 to 1927, German physicist W. Heisenberg (1901-1976), the Austrian physicist E. Schrodinger (1887-1961) and L. de Broglie (1892- 1987), established a new mechanical system—quantum mechanics—to describe the microscopic world. Analogously, the status of quantum mechanics in the microscopic world is equivalent to the status of Newtonian mechanics in the macroscopic world.

Taking the hydrogen atom as an example, the atomic structure in quantum mechanics is fundamentally different from the assumptions of Bohr's theory. Based on quantum mechanical theoretical calculations, the electron orbit is just a place where the probability of electrons appearing is high. The movement of electrons outside the nucleus is usually described vividly as an "electron cloud". That is to say, the nucleus seems to be shrouded in a layer of clouds. Where the cloud concentration is high, electrons are more likely to appear; where the cloud concentration is low, electrons are less likely to appear.

Quantum mechanics has successfully explained a large number of phenomena that Bohr's theory cannot explain. The basic assumptions of Bohr's theory paved the way for the inevitable theoretical derivation in quantum mechanics. In addition, quantum mechanics has helped scientists explain the details of atomic structure, atomic spectra, and chemical bonds. Later, with the contributions of many scientists (such as Dirac, Fermi, Born, etc.), this quantum theoretical system became more complete.

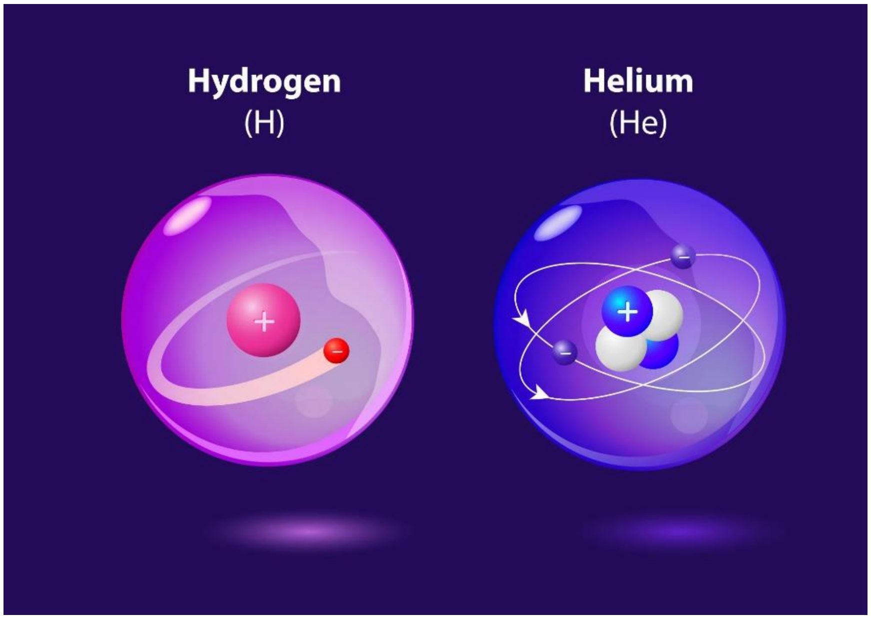

Figure 6.3 Models for Hydrogen and Helium atoms in quantum mechanics adapted from https://www.azoquantum.com/Article.aspx?ArticleID=232

6.3, Isotope, Decay of radioactive elements and half life

The nucleus is made up of protons and neutrons. What is the relationship between the symbol A,Z, and X of the atomic nucleus and the number of protons and neutrons?

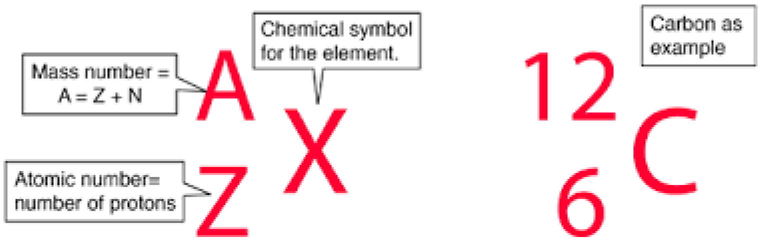

Figure 6.4 Mass number and atomic number diagram adapted from https://theory.labster.com/mass-number-and-atomic-number/

Protons are positively charged, and each proton carries a charge of 1 element. If there are Z protons in a certain nucleus, then it has a charge of Z elements. Therefore, the Z in the lower left corner of the atomic symbol is the atomic number of the element, that is, the charge amount expressed as a multiple of the number of protons. For example, the uranium nucleus has 92 protons, so the atomic number of the uranium nucleus is 92, that is, Z=92 as shown in Figure 6.5. The number of protons---the atomic number determines what type of atoms we are looking into. For examples, all carbon atoms must have 6 protons.

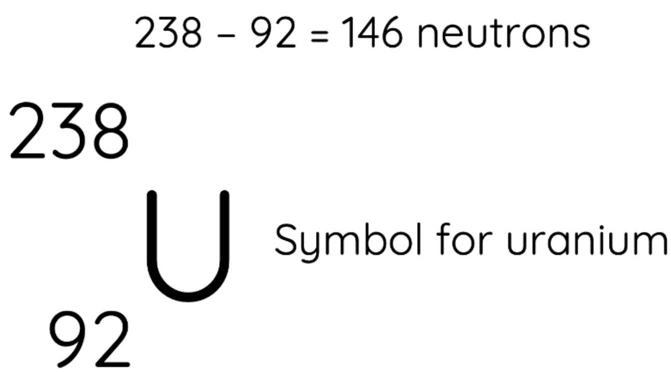

Figure 6.5 Atomic number of U adapted from https://scienceready.com.au/pages/nuclear-stability

The number of neutrons for a given element can be different. The same atoms with different number of neutrons are called isotopes. For instance, neutrons can be 6, 7 or 8 in Carbon's isotopes as shown in figure 6.6. For instance, what is the difference between ${}^{12}_{6}C$ and ${}^{14}_{6}C$? They have the same number of protons, that is, the same number of electrons outside the nucleus, so they have the same chemical properties and belong to the same element - carbon. But their neutron numbers are different. ${}^{14}_{6}C$ has two more neutrons than ${}^{12}_{6}C$ and is radioactive**.** Elements with the same nuclear charge and different numbers of neutrons are called isotopes. Radioactive isotopes are called radioactive isotopes. For example**,** ${}^{2}_{1}$H (deuterium), ${}^{3}_{1}$H (tritium) and ${}^{1}_{1}$H (hydrogen) are isotopes. Another example ${}^{234}_{92}$U, ${}^{235}_{92}$U and ${}^{238}_{92}$U are also isotopes.

When Joliot Curie and his wife bombarded aluminum foil with alpha particles, in addition to detecting neutrons, they also detected positrons (positrons have the same mass as electrons and carry a unit positive charge, with the symbol ${}^{0}_{1}e$). After removing the alpha particle source, the aluminum foil no longer emitted neutrons, but it continued to emit positrons. Joliot Curie and his wife found that positrons are emitted from the newly generated phosphorus nucleus. The nuclear reaction equation of alpha particles bombarding the aluminum nucleus is:

$$^{27}_{13}Al + ^{4}_{2}He \rightarrow ^{30}_{15}P + ^{1}_{0}n.$$

The newly generated $^{30}_{15}P$ is an isotope of phosphorus. It is radioactive and has a certain half-life. Its decay equation is:

$$^{30}_{15}P \rightarrow ^{30}_{14}Si + ^{0}_{1}e.$$

Man-made approach could be adopted to obtain radioactive isotopes, which was an important discovery in nuclear history and produces more than 1,000 radioactive isotopes by man-made approach.

The number of protons and the number of neutrons together are called an element's mass number: mass number = protons + neutrons. An element's mass number determines its atomic mass. The atomic mass is defined as the atom's total mass in atomic mass units or amu. By default, a carbon-12 atom with 6 neutrons has an atomic mass of 12 amu. Other atoms not necessarily have an integer in their atomic mass, but very close to their mass number (with some deviation in decimal places). Because the isotopes of an element have different atomic masses, a relative atomic mass (also called the atomic weight) for an element is defined as an average of atomic masses of all the different isotopes in nature.

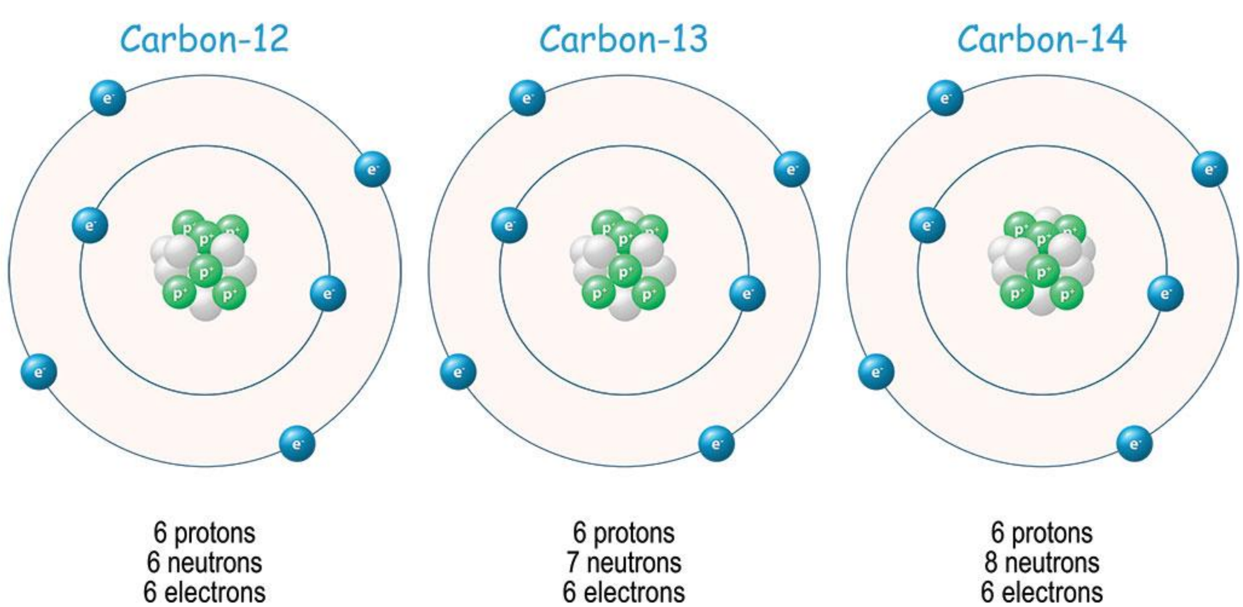

Figure 6.6 isotopes of Carbon adapted from https://www.snexplores.org/article/fossil-fuels-confusing-carbon-isotope-dating-measurements

Every atom tries to stay as stable as possible. When an imbalance in the number of protons and neutrons in the atomic nucleus occurs, there is too much energy inside the nucleus to hold all the nucleons together causing instability in form of radioactive decay. The process of an unstable atomic nucleus losing energy through radiation is called radioactive decay. A material with unstable nuclei is considered radioactive. Of the 118 elements on the periodic table, there are 94 elements naturally existing. While there are 254 stable isotopes, there are more than 3,000 known radioactive isotopes, only 84 of which are found in nature.

Although the spontaneous radioactivity of each nucleus of radioactive element sounds like random, researchers have found that the speed of a large number of nuclear decays has certain rules. People experimented with the alpha decay of $^{222}_{86}Rn$ (radon nucleus) and found that approximately every 3.8 days, half of the radon nuclei decayed. After another 3.8 days, the number of Radon was reduced to the original ¼. Therefore, the time taken for the radioactivity of a specified isotope to fall to half its original value is called half-life.

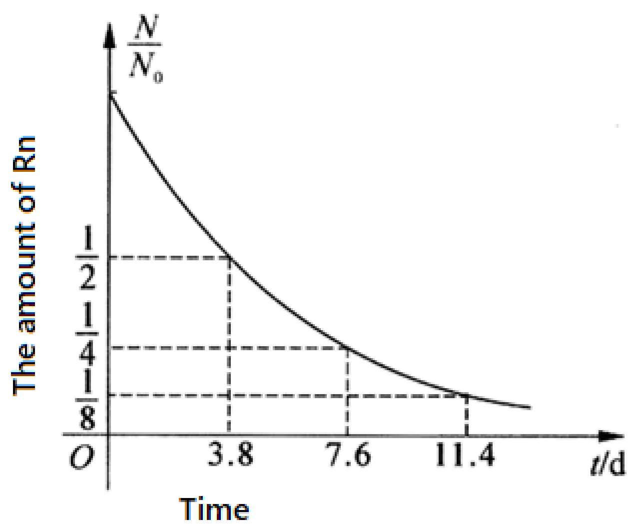

Figure 6.7 Half life of Rn adapted from https://enjoyphysics.cn/Article2590

We use half-life to express the speed of decay of radioactive elements. The time required for half of the nuclei of radioactive elements to decay is called the half-life of this element. The half-lives of different radioactive elements are very different as shown in Table 1, in which the decay types and half-lives of some elements are displayed. The rate of decay of radioactive elements is determined by factors within the nucleus and has nothing to do with the physical or chemical states of the atom, for instance, whether a radioactive element exists in an elemental form or a compound form, whether it is pressurized, heated or treated in any other way, generally its half-life cannot be changed. Because none of the above factors have an impact on the nucleus itself, which explains why radioactive elements can be used as tracer atoms, and it is also one of the reasons why nuclear pollution is difficult to eliminate.

radioactive elements	types of decay	half life
${}^{3}_{1}H$	β	12.33 years
${}^{14}_{6}C$	β	5730 years
${}^{32}_{15}P$	β	14.3 days
${}^{38}_{17}Cl$	β, γ	37.3 minutes

Table 1. half life of several radioactive elements

6.4. **Types of radioactivity**

Radioactive isotopes emit active radiation and come in various types, the most common being alpha (alpha), beta (beta) and gamma (gamma) radiation.

a. Alpha decay

The decay of an atomic nucleus spontaneously emitting alpha particles is called alpha decay. Since the radioactive atomic nucleus ${}^{A}_{Z}X$ undergoes an alpha decay, one alpha particle (${}^{4}_{2}He$) is missing, so the mass number is reduced by 4 and the charge number is reduced by 2, becoming a new nucleus ${}^{A-4}_{Z-2}Y$. We can write a decay equation to express the changes before and after decay:

$${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$$

For example, after alpha decay of ${}^{238}_{92}U$ (uranium nucleus), the mass number of the nucleus is reduced by 4, the charge number is reduced by 2, and the new nucleus becomes a thorium 234 nucleus as shown in Figure 6.8. The decay equation is written as follows:

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

In the above decay process, the mass number before decay is equal to the sum of the mass numbers after decay; the charge number before decay is equal to the sum of the charge numbers after decay. A large number of facts show that both the charge number and the mass number are conserved when the nucleus decays.

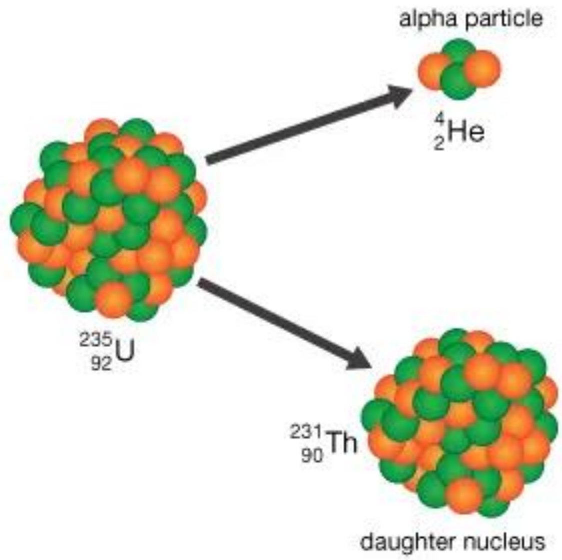

Figure 6.8 alpha decay adapted from https://school.eb.co.uk/?target=%2Flevels%2Fadvanced%2Fassembly%2Fview%2F253724

b. Beta decay

The decay of an atomic nucleus spontaneously emitting beta particles is called beta decay as shown in Figure 6.9.

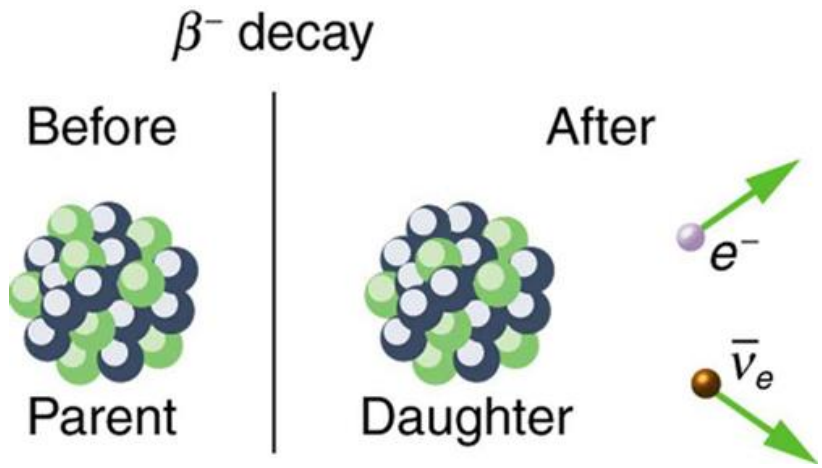

Figure 6.9 Beta decay adapted from https://socratic.org/questions/what-would-the-nuclear-equation-be-for-the-beta-decay-of-strontium-90

For example, after beta decay of ${}^{234}_{90}Th$ (thorium), the mass number of the nucleus remains unchanged. Because the mass of the electron is very small, only $\frac{1}{1840}$ of the proton, it can be ignored. The charge number is -1, and the new nucleus becomes protactinium with 234. The decay equation is written as follows:

$${}^{234}_{90}Th \rightarrow {}^{234}_{91}Pa + {}^{0}_{-1}e.$$

The mass number and charge number are also conserved on both sides of this equation.

When the nucleus of a radioactive element undergoes alpha decay or beta decay to generate a new nucleus, it often puts the nucleus in a high-energy state. When it converts from a high-energy state to a low-energy state, it radiates gamma photons, so alpha decay and beta decay are often accompanied by gamma radiation.

C. Gamma decay

The nucleus of an atom emits high-energy, short-wavelength, electromagnetic radiation is called gamma radiation as shown in figure 6.10.

When an atom undergoes gamma radiation, the frequency of the released gamma radiation could be possibly determined if the energy of initial and final states of the nucleon are given. The frequency of gamma radiation can be written as follows:

$$E_i - E_f = hf$$

In which E_i is the initial, higher energy state of the nucleon; E_f is the final, lower energy state of the nucleon; h is Planck's constant; and f is the frequency of the emitted radiation.

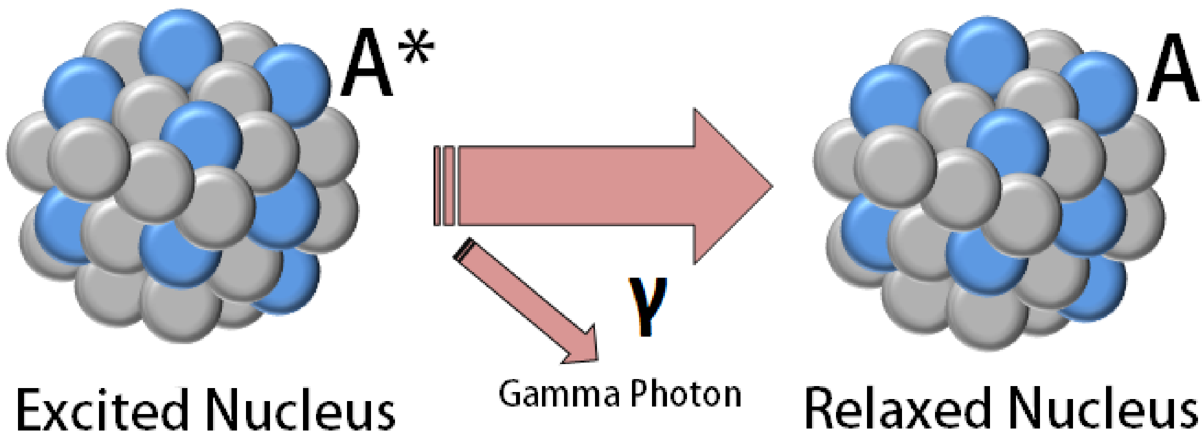

Figure 6.10 gamma decay adapted from
https://energyeducation.ca/encyclopedia/Gamma_decay

6.5 **Discovery of neutron**

In 1930, scientists discovered that when alpha particles emitted by the radioactive element polonium (Po) bombarded beryllium (Be), an invisible ray was produced. It is composed of uncharged neutral particles. In 1932, Joliot Curie and his wife also conducted this experiment and bombarded hydrogen-containing paraffin with this unknown ray. They found that protons with huge energy were released, so they believed that those neutral particles are gamma photons with great energy.

Rutherford's student Chadwick (1891-1974) had read the article of Joliot Curie and his wife. Through careful analysis, he immediately repeated the same experiment and found that the speed of this neutral ray was less than $\frac{1}{10}$ of the speed of light. Based upon the conservation of momentum and energy, its mass was calculated approximately equal to the mass of the proton. Chadwick published his result in the journal “Nature” on February 17, 1932, and named this neutral particle a neutron, represented by the symbol ${}_0^1n$. Then Neutron was born! It is a component of the atomic nucleus. This discovery is another important transformation of atomic nuclei. The nuclear reaction equation that produces "beryllium radiation" is:

$${}_{2}^{4}He + {}_{4}^{9}Be \rightarrow {}_{0}^{1}n + {}_{6}^{12}C.$$

Chadwick won the 1935 Nobel Prize in Physics by the discovery of the neutron, but Joliot Curie and his wife missed out on the Nobel Prize in Physics due to their misjudgment.

6.6 **Einstein's E=m*C²**

The radius of the atomic nucleus is only 10^{-15}~10^{-14} m. When the protons and protons get too close, the Coulomb repulsion would be very strong. However, the atomic nucleus is usually very stable, suggesting that in the nucleus, in addition to the Coulomb force between protons, there is another force. We call this force the nuclear force. What are the characteristics of nuclear force? First, nuclear forces have nothing to do with whether nuclei are charged or not. In other words, there are nuclear forces between protons and protons, protons and neutrons, and neutrons and neutrons. Secondly, when the distance between nuclei is 0.8×10^{-15}~2.0×10^{-15}m, the nuclear force is a very strong attraction, more than 100 times greater than the Coulomb force, which is enough to overcome the electrostatic repulsion and bind the nuclei tightly together. But the nuclear force only works within a short distance. When the distance between two nuclei is greater than 5.0×10^{-15} m, the nuclear force quickly disappears. The radius of protons and neutrons is about 0.8×10^{-15}m, so each nucleon only experiences nuclear force from adjacent nucleons in the nucleus.

Binding energy

The nuclear force in the atomic nucleus tightly binds the nuclei together. To separate the nuclei, one must overcome the nuclear force and do work, or in other words, give the nucleus a huge amount of energy. For example, it is necessary to irradiate a deuteron with gamma photons with an energy of about 2.22 MeV to decompose it into a proton and a neutron. The nuclear reaction equation can be written as:

$$\gamma + {}_{1}^{2}H \rightarrow {}_{1}^{1}H + {}_{0}^{1}n$$

On the contrary, if a proton and a neutron are combined into a deuterium, 2.22 MeV of energy will be released. This energy will be radiated in the form of gamma photons. The equation is:

$${}_{1}^{1}H \ + {}_{0}^{1}n \rightarrow {}_{1}^{2}H + \gamma$$

The energy is released when nucleons are combined into atomic nuclei, or the energy is absorbed when atomic nuclei are decomposed into nucleons, is called the binding energy of the nucleus. The usually called nuclear energy is part of the binding energy.

The stability of the nucleus depends on the average binding energy (specific binding energy) of the nucleus. If ΔE is used to represent the binding energy and A represents the number of nucleons, then the average binding energy is $\frac{\Delta E}{A}$. The average binding energy of light and heavy nuclei is smaller, while the average binding energy of medium-mass nuclei is larger, indicating that medium-mass nuclei are relatively stable.

Mass loss

Physicists have found that when a proton and a neutron combine to form a deuteron, they not only release energy but also reduce their mass. That is to say, the sum of the masses of the proton and neutron is greater than the mass of the deuteron. When nucleons form a nucleus, the difference between the mass of the nucleon and the mass of the nucleus is called mass loss.

Example:

When 2 neutrons and 2 protons combine to form a helium nucleus, the nuclear reaction equation is as follows:

$$2{}_0^1n + 2{}_1^1\mathrm{H} \rightarrow {}_2^4\mathrm{He}.$$

The mass of the neutron is m_n=1.008 665 u, the mass of the proton is m_H=1.007 825 u, and the mass of the helium nucleus is m_{He}=4.002 600 u. Find the mass lost when the neutron and proton form a helium nucleus.

Solution:

The mass of the starting materials =2*(m_n+ m_H)=2*(1.008 665 u+1.007 825 u)= 4.032 980 u

The mass of the ending material =4.002 600 u

The mass loss Δm=4.032 980 u−4.002 600 u=0.030 38 u.

Albert Einstein was the first scientist to establish the connection between mass and energy. After publishing the theory of relativity, Einstein proposed in the "Postscript" that the energy of an object is proportional to its mass, or energy E is equal to the product of mass m and the square o the speed of light c, that is

$$E = m * c^2$$

This equation is called Einstein's mass-energy equation.

The above equation is written as the relationship between mass loss and energy release, which is:

$$\Delta E = \Delta m^{*} \cdot c^2$$

Use this equation to calculate the energy that should be released by an α particle composed of 4 nuclei:

$$\Delta E = \Delta m \cdot C^2 == 0.030\ 38 \times 1.66 \times 10^{-27} \times (3.00 \times 10^8)^2\ J$$

$$= 4.539 \times 10^{-12} J = 28.37 MeV.$$

When nuclei combine to form 1 mol of helium nuclei (about 4 g), approximately 2.73×10^{12}J of energy will be released, which is equivalent to the energy released by burning 100 tons of coal. This shows how huge the energy released by nuclear reactions is. There is also mass loss during the fission of heavy nuclei, and the huge energy released can also be calculated using the mass-energy equation.

6.7 **Nuclear reactions**

a. Fission reactions

Nuclear fission and nuclear fusion are rare processes that can convert mass into energy. Currently the energy released only from nuclear fission can be utilized by human being. So, what is the process of a nuclear fission?

Nuclear fission refers to the process in which a heavier atomic nucleus splits into two or more medium-mass or smaller nuclei through a nuclear reaction. The fission process often produces gamma photons, and releases a very large amount of energy even by the energetic standards of radioactive decay. Not all atomic nuclei can undergo nuclear fission. Only nuclei that are unstable due to excessive mass will undergo fission. Nuclear fission is divided into spontaneous fission and induced fission. As the name suggests, spontaneous fission means that the nucleus is very unstable and can spontaneously fission into two more stable medium-mass nuclei. Induced fission requires artificial provision of some energy or stimulation to stimulate instability. The nucleus becomes more unstable and fission occurs.

For example, the fission of ${}^{235}_{92}U$ is varying. One typical fission is to produce barium (Ba) and krypton (Kr), and simultaneously release 3 neutrons. The nuclear reaction equation is:

$${}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3\ {}^{1}_{0}n$$

If neutrons can continuously bombard ${}^{235}_{92}U$, nuclear energy can be continuously released. While the nuclear fission of ${}^{235}_{92}U$ releases huge energy, an average of 2 to 3 neutrons can be released each time. These neutrons are called first-generation neutrons. If at least one of them continues to bombard $^{235}_{92}U$, causing it to fission, can produce second generation neutrons. If this continues, the number of neutrons will continue to increase and the fission reaction will continue to form a chain reaction of fission (chain reaction). Fusion reactions are shown in Figure 6.11.

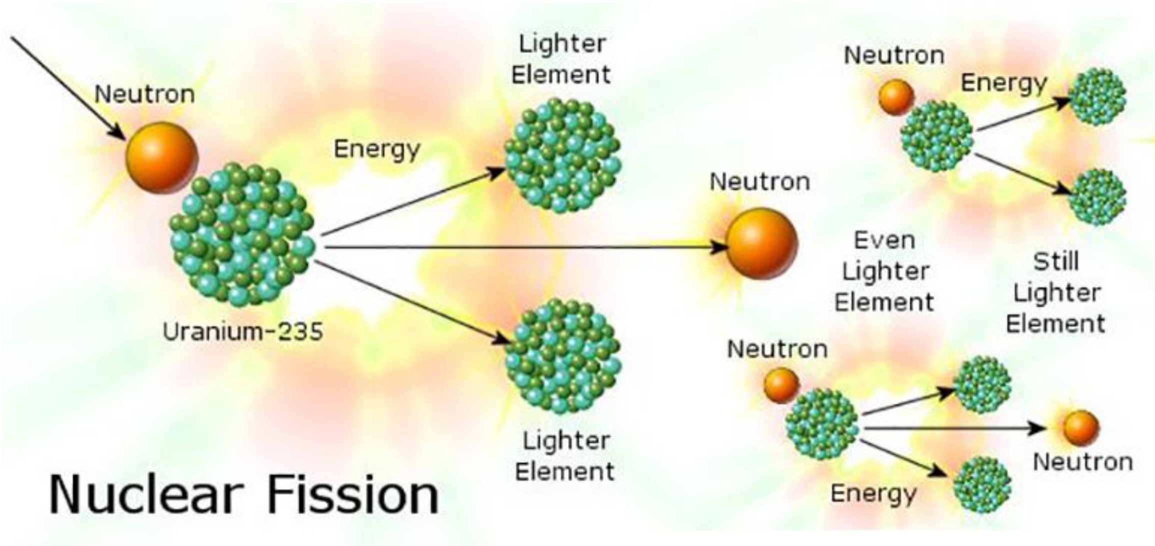

Figure 6.11 a chain reaction of nuclear fission, adapted from https://nrl.mit.edu/reactor/fission-process

In nature, the sun and many stars are undergoing a nuclear reaction, which is called nuclear fusion. By observing the corona on the surface of the sun, it is like a sea of fire, rolling with flames. Its surface temperature is 6×10^{3}°C, and its internal temperature can reach 3×10^{7}°C. What is going on inside the sun is the process of combining lighter atomic nuclei (such as deuterium, tritium, etc.) into new atomic nuclei, thus releasing a large amount of binding energy.

b. Fusion reactions:

Heavy nuclei can release huge amounts of energy when they fission. When certain light nuclei with very small masses combine to form larger nuclei, they can also release huge amounts of energy. When the same mass of nuclear fuel is consumed, the energy released by the fusion of light nuclei is greater than that of the splitting of heavy nuclei. For example, when two deuterons combine to form one tritium nucleus, a binding energy of 4 MeV is released. The nuclear reaction equation is:

$$^{2}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{1}H + ^{1}_{1}H.$$

Another example: when a deuteron and a tritium combine to form a helium nucleus, a binding energy of 17.6 MeV is released as shown in Figure 6.12. The nuclear reaction equation is:

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}H + ^{1}_{0}n.$$

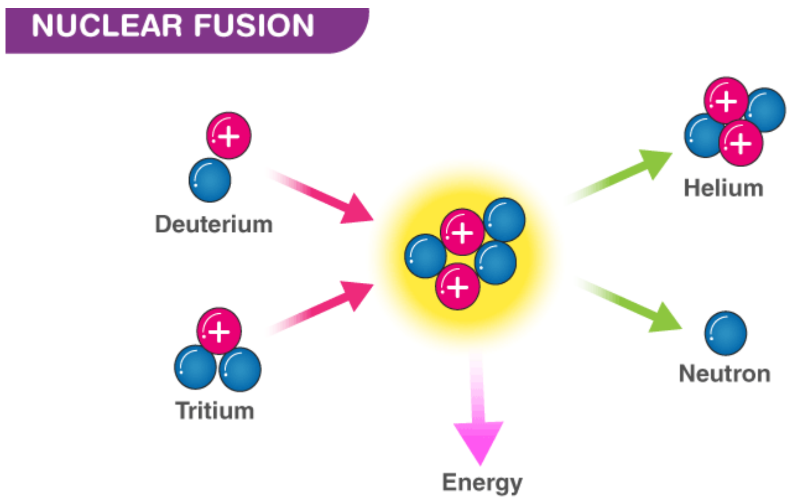

Figure 6.12 Nuclear fusion reaction adapted from https://byjus.com/physics/nuclear-fusion/

The combination of light nuclei into larger nuclei is **called fusion**. It can be seen from the above example that the average binding energy released by each nucleon during fusion is much greater than the average binding energy released by each nucleon during heavy nuclear fission.

C. Thermonuclear reaction:

Light nuclei must be close to where nuclear force can act before fusion can occur. Due to factors such as Coulomb repulsion, light nuclei must have sufficient kinetic energy to be close to each other. Theoretical research points out that only at high temperatures of several million degrees, the atoms are completely ionized, and all the extranuclear electrons of the atoms are detached from the atoms and become plasma. At this time, some atomic nuclei have enough kinetic energy to overcome the Coulomb repulsion between each other and collide. To the extent that fusion occurs, this reaction is called a thermonuclear reaction as shown in figure 6.13.

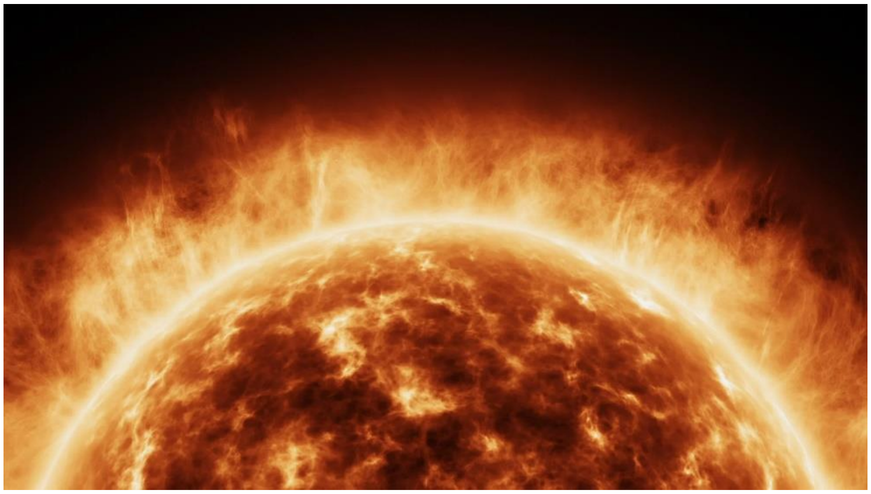

Figure 6.13-star surface, thermonuclear reaction adapted from https://www.pond5.com/stock-footage/item/89738696-star-surface-thermonuclear-reaction-smooth-zooming

Currently the thermonuclear reaction on earth is a hydrogen bomb explosion. A hydrogen bomb is a combination of an atomic bomb and thermonuclear fuel as shown in Figure 6.14. The high temperature of the atomic bomb explosion is enough to cause a thermonuclear reaction. Except for hydrogen bombs, people have no yet way to control fusion reactions and utilizing fusion energy. Thermonuclear reactions have many advantages over fission reactions. First of all, in terms of the energy released, for the same mass of nuclear fuel, fusion releases much more energy than fission. Secondly, the radioactive material produced by fission is more difficult to deal with, whereas thermonuclear reactions present a much simpler problem in this regard. In addition, deuterium, the fuel for thermonuclear reactions, is very abundant on the earth. There is a large amount of deuterium in seawater. There are about 0.03 g of deuterium in 1L of seawater. Using it for thermonuclear reactions releases as much energy as burning 300 L of gasoline.

Figure 6.14. an image of a hydrogen bomb explosion adapted from https://www.cnbc.com/2016/01/06/cnbc-explains-what-is-a-minitiarized-hydrogen-bomb.html

Controllable thermonuclear reactions are still in the early stage around the world. An "International Thermonuclear Experimental Reactor Program" has been launched, with participating countries including 15 EU member states, the United States, Russia, Japan, South Korea, Canada and China. The program aims to establish the world's first near-practical fusion experiment Reactor. It is believed that mankind will be able to realize the grand ideal of controllable thermonuclear fusion.

6.8 **Nuclear Applications:**

Countries around the world are actively developing the theory and technology of controllable nuclear fusion. Currently, two approaches are most investigated. One method is called magnetic confinement, and the other is called laser inertial confinement. Magnetic confinement uses a magnetic field to confine high-temperature plasma in a certain space for a long enough time to reach the so-called "ignition" condition (the condition for fusion energy to proceed automatically as shown in Figure 6.15. It is a device called "Tokamak". A central annular vacuum chamber is filled with deuterium gas, and a coil is wound outside the vacuum chamber. After being energized, a spiral magnetic field is formed and a high voltage of up to 106A is generated. Axial current heats the plasma. Laster inertial confinement is as showed in Figure 6.16. Inertial confinement fusion (ICF) is a fusion energy process that initiates nuclear fusion reactions by compressing and heating targets filled with fuel.

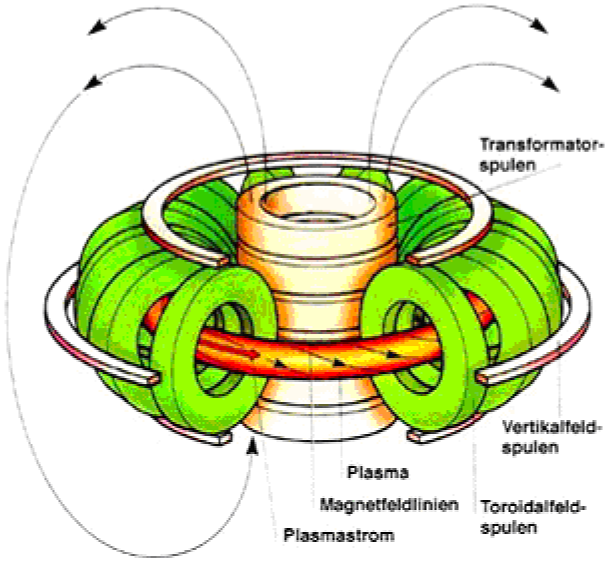

Figure 6.15 the Tokamak device, adapted from
https://www.euronuclear.org/glossary/tokamak/

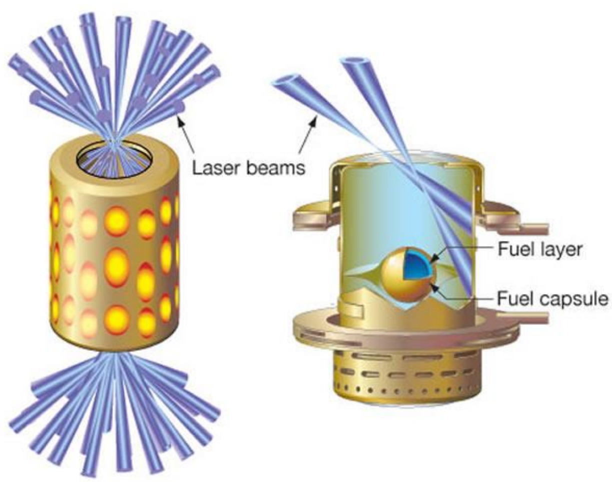

Figure 6.16 the device of laser inertial confinement adapted from https://lasers.llnl.gov/science/icf

Nuclear physics is important for human beings to understand the material world. The atomic nucleus is a quantum many-body system composed of several to hundreds of nucleons. It is a fertile playground for studying strong interactions and Coulomb interactions. Nuclear physics mainly studies the structure of atomic nuclei, decay, and atomic collision between nuclei. Nuclear physics holds huge potential in various applications. Nuclear energy is important to national security and energy security. The fission of heavy nuclei releases several neutrons and a large amount of energy at the same time, which was successfully used to develop the atomic bomb, which ended World War II. Strategic nuclear weapons essential to a country's arm force for external deterrence that goes beyond conventional armaments. Nuclear radiation detection technology is to study and utilize the interaction between rays and matter. In recent years, the complexity and sophistication of nuclear detection equipment has continuous improvement, which becomes the key to nuclear scientific research and application. Nuclear detectors look intro the different types of signals produced by interaction of the radiation and the material, which can be categorized into gas detectors, scintillator detectors, semiconductor detectors, etc. Research can only be detected through detectors, opening up the continuous updating and development of particle accelerators and particle detectors. Experiments and theories complement each other and promote human understanding of the material world, which is also far from the traditional approaches.

In the agricultural field, nuclear technology is widely used in plant radiation mutation breeding, agricultural modernization, products and food radiation processing, agricultural nuclide tracing, stable isotope tracing, basics of radiobiology and insect radiation sterility, etc.

Possible medical applications of this new science like the therapeutic effects of radioactive rays on certain diseases were discovered. With a wide range of applications, including but not limited to proton cancer treatment, heavy ion cancer treatment, magnetic resonance imaging, positron emission tomography imaging, radiation elimination poison, particle scalpel, radioactive tracer technology, radioactive nuclear beam targeted drugs, etc. Nuclear technology also plays a role in archaeology, environmental governance and other fields. For example, archaeological surveying is based on radiocarbon dating, characteristic radiation excitation is based on proton irradiation or X-ray irradiation. With the development of the theory and technology, nuclear technology would find more and more applications in our daily life.

Exercises:

1. What is the key concept of the Bohr model?

2. What is the proton number for silver?

3. What is the maximum number of electrons in the Bohr model's second shell?

4. Define the isotopes.

5. What number of protons are emitted in Alfa radiation?

6.How many neutrons are emitted in beta radiation?

7. What type of radiation would be the most difficult to shield?

8. When an atom emits a beta particle, how does the mass number change?

9. What type of nuclear reaction does a nuclear plant use?

10.What is the advantage of fission versus fusion?

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