普通高等教育核工程与核技术专业规划教材

HEDIAN ZHUANYE YINGYU

核电专业英语

阎昌琪 编

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内容提要

本书为普通高等教育核工程与核技术专业规划教材。

本书的内容涵盖了与核电有关的基础理论知识和专业知识，介绍了反应堆结构、核动力系统和设备，也包括了近年来核电的新发展，例如第三代和第四代反应堆的介绍。书中涉及的核电专业词汇广泛、内容丰富、知识性强。

为了便于读者掌握专业词汇，每课课文后对重要的关键词作了英、中文两种解释，同时还列出了重要的词汇解释、课文中的难点注释。为了加深读者对课文内容的理解，课后还附有习题和答案。

本书可作为普通高等教育本科核工程与核技术专业的英语阅读教材，也可作为核电工程技术人员的培训和自学用书，同时可作为能源动力类等相关专业人员的阅读材料。

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前　言

核电工程技术涉及的学科领域广泛，包含很多高新技术。目前，美、英等发达国家在该领域处于领先地位，很多新的研究成果和新技术的介绍都以英文发表，每个从事核电工程研究、设计和运行的专业人员都需要阅读大量的英文资料。为了满足越来越多的核电工程专业人员学习专业英语的需要，编写了本书。

本书内容涵盖了核电工程所涉及的主要学科，在介绍核反应堆物理及核反应堆热工等基础知识的同时，也介绍了各种类型的核反应堆及主要设备的原理和使用特性等。主要内容包括：核反应堆物理的基础知识、核材料、核反应堆热工水力学、反应堆结构、核动力系统和主要设备、核反应堆运行及核安全、核动力的发展及新一代反应堆等。本书内容广泛，选用不同风格的文章，做到内容新、知识面宽；选用的课文概念性和知识性强、难度适中，不涉及复杂的专业理论。为了便于读者掌握专业词汇，每课课后对重要的关键词作了英、中文两种解释，同时还列出了重要的词汇解释、课文中的难点注释。为了加深读者对课文内容的理解，课后还附有习题和答案。

本书的内容安排由浅入深、由基础到专业，可适合不同层次的学生使用。全书围绕着核电工程这一主题，在专业部分中以新一代压水堆核电站动力装置为主线，介绍了目前运行的核电技术以及新一代的核电技术。书中的每一课都有相当的独立性，可以根据学生的兴趣和专业方向选择使用，同时也考虑了课文内容满足总体需要，保证全书内容是一个完整的整体。

本书的阅读内容取自英文的原版教科书和工程设计说明书。书中的引文，编者尽力与版权所有者取得联系，但仍有部分联系不上，在此深表歉意。

全书共20个单元，由哈尔滨工程大学阎昌琪教授编写，由中国原子能科学研究院阮於珍研究员主审，阮老师提出了许多宝贵的意见和建议，在此深表谢意。

由于编者水平所限，书中难免存在缺点和不足，敬请读者提出宝贵意见。

编　者

2010年5月

目　　录

Unit 1 The Basic Concepts for Nuclear Physics

1.1 Atoms and Nuclei

The atoms of all elements, which at one time were thought to be the fundamental particles of nature, consist of numbers of three more fundamental particles-protons, neutrons and electrons. The arrangement of these particles within the atom, and in particular the number of protons and electrons, determine the chemical identity of the element. The atom consists of nucleus in which all the positively charged protons and uncharged neutrons are closely grouped together, and a number of negatively charged electrons moving in orbital paths around the nucleus. In an electrically neutral or unionized atom, the number of protons is equal to the number of electrons, and this number, Z, is the atomic number of a particular element and identifies it. (This number corresponds to the position of the element in the Periodic Table.) The number of neutrons in the nucleus is denoted by N, and the sum of the number of neutrons and protons in the nucleus is called, for reasons that will shortly be apparent, the mass number, A.

$$N + Z = A$$

The term nucleon is applied to all particles, both protons and neutrons, in the nucleus.

Fig.1.1 is a useful, though not strictly accurate representation of an atom of carbon with six protons and six neutrons in the nucleus, and six orbital electrons. To be more accurate, the radius of the innermost electron orbit should be about ten thousand times the radius of the nucleus.

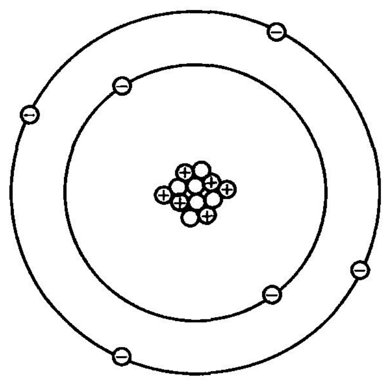

Fig.1.1 atomic structure of carbon 12

1.2 Isotopes

Atoms having the same atomic number, Z, but different numbers of neutrons N are called isotopes of the element identified by Z, and all elements have a number of isotopes, in some cases twenty or more. The naturally occurring elements each have one or more stable isotopes which exist naturally, and other isotopes which are unstable or radioactive and can be produced by artificial means. Different isotopes of an element behave identically as far as their chemistry is concerned, which is not surprising as chemical bonds exist between electrons. Isotopes differ from one another physically in that the masses and other characteristics of their nuclei are different, which is to be expected as it is in the nuclei that the difference between two isotopes lies[1].

The complete identification of an isotope is made by giving its chemical symbol, the atomic number Z as a subscript and the mass number A as a superscript. For example, the symbol $^{16}_{8}O$ identifies the isotope of oxygen that has eight protons and eight neutrons in its nucleus. The isotope $^{17}_{8}O$ has eight protons and nine neutrons in its nucleus. Naturally occurring oxygen consists of a mixture of three isotopes, $^{16}_{8}O$, $^{17}_{8}O$ and $^{18}_{8}O$. There are also three radioactive isotopes of oxygen which do not occur naturally. The subscript Z is in fact unnecessary as the name oxygen identifies that element with eight protons in its nucleus and the symbols may be written as ^{16}O, ^{17}O and ^{18}O.

Hydrogen is an important element in nuclear engineering. Naturally occurring hydrogen consists of two isotopes, 99.985 percent of the isotope ^{1}H and 0.015 percent of the isotope ^{2}H called heavy hydrogen or deuterium. There is a third isotope ^{3}H called tritium which is radioactive. This is the only case in which the different isotopes of an element have different names. Usually they are identified by their mass numbers.

1.3 Mass Defect

The mass of atom is not equal to the sum of the masses of its constituent particles. For example the mass of the ^{16}O atom is obviously less than the sum of the masses of eight neutrons and eight hydrogen atoms. Somewhere in the process of building the atom with its constituent particles the classical principle of conservation of mass appears to have been violated, and the difference between the mass of an atom and the sum of the masses of its constituent particles is known as the mass defect.

The explanation is to be found in the principle of the equivalence of mass and energy in which Einstein stated that mass and energy are different forms of the same fundamental quantity [2]. In many reactions there is an interchange of mass and energy so that, particularly on an atomic scale, the laws of conservation of mass and conservation of energy are not valid when applied separately to a reaction, and must be replaced by the law of conservation of mass plus energy. In any reaction in which mass changes, a decrease of mass is accompanied by the release of energy, and an increase of mass corresponds to the absorption of energy.

The equivalence between mass and energy is expressed by the famous equation:

$$E = mc^2$$

where c—the speed of light, 2.998×10^{8}m/s.

1.4 Binding Energy

The force of electrostatic repulsion between like charges, which varies inversely as the square of their separation, would be expected to be so large that nuclei could not be formed. The fact that they do exist is evidence that there is an even larger force of attraction. This nuclear force acts only when the nucleons are very close to each other and binds them into a compact stable structure. Associated with the net force is a potential energy of binding. To disrupt a nucleus and separate it into its component nucleons, energy must be supplied from the outside. Recalling Einstein's relation between mass and energy, this is the same as saying that mass must be supplied to the nucleus. A given nucleus is lighter than the sum of its separate nucleons, the difference being the binding mass-energy. Let the mass of an atom including nucleus and external electrons be M, and let m_n and m_H be the masses of the neutron and the proton plus matching electron. Then the binding energy is B=total mass of separate particles-mass of the atom or

$$B=Nm_n+Zm_H-M$$

(Neglected in this relation is a small energy of atomic or chemical binding.) Let us calculate B for tritium, the heaviest hydrogen atom. Fig.1.2 shows the dissociation that would take place if a sufficient energy were provided. Now Z=1, N=2, m_n=1.008 665, m_H=1.007 825, and M=3.016 049. Then

$$B=2(1.008\ 665)+1(1.007\ 825)-3.016\ 049=0.009\ 106(\text{u})$$

Converting by use of the relation 1u=931MeV, the binding energy is B=8.48MeV. Calculations such as these are required for several purposes to compare the stability of one nucleus with that of another, to find the energy release in a nuclear reaction, and to predict the possibility of the fission of a nucleus.

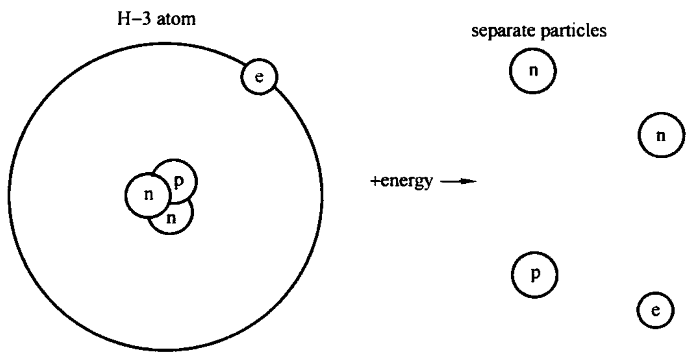

Fig.1.2 dissociation of tritium

We can speak of the binding energy associated with one particle such as a neutron. Suppose that M_1 is the mass of an atom and M_2 is its mass after absorbing a neutron. The binding energy of the neutron of mass m_n is then

$$B_n=M_1+m_n-M_2$$

1.5 Energy Levels

Normally atomic nuclei exist in an equilibrium or stable condition known as their ground state of energy. However, as a result of nuclear reactions (which might be caused by the bombardment of atoms by protons, neutrons or other light particles), nuclei can be produced in an excited or unstable condition in which one or a number of nucleons are raised to an excited state. The excited states or levels in a nucleus are similar to the excited state of atoms. In the case of the latter, excitation results in an electron jumping from its normal orbit to another orbit further from the nucleus, and an atom may have a number of discrete excited states corresponding to an electron having made one or more such jumps. In the nucleus the situation is more complicated because excitation can result in several nucleons being raised to excited levels simultaneously, and some nuclei can have a very large number of closely spaced excited levels. In general light nuclei have more widely spaced excited levels, and in all nuclei the spacing of the levels decreases as the excitation energy increases.

Most excited nuclei exist in this state for only a very short time, a typical average lifetime being about 10^{-14} seconds, and they decay, or become de-excited, by the emission of high energy electromagnetic radiation known as gamma radiation, or particles such as neutrons, or both. In most reactions of interest to nuclear engineers involving the formation and decay of excited nuclei, the lifetime of the excited nucleus is so short that the process of formation and decay can be regarded as instantaneous.

1.6 Fission

The discovery of fission was made in Germany in 1938 by Hahn[3] and Strassmann who were studying the radioactive isotopes formed as a result of the bombardment of uranium by neutrons in an effort to produce transuranium elements. One of the elements identified in the products of the reactions was radioactive barium 139, which indicated a hitherto unknown type of reaction in which the uranium nucleus split into fragments which were themselves nuclei of intermediate mass elements. Further work showed the presence of several other elements of medium mass number, and the existence of the fission process was definitely established. Shortly afterwards it was shown that neutrons were also emitted in the process and the possibility of a chain reaction was realized in which neutrons emitted in one fission event might be able to cause further fission, thus establishing a continuous reaction.

The isotope of uranium that is principally responsible for fission is ^{235}U, which is present in naturally occurring uranium to the extent of 0.715 percent. In this isotope fission can be caused by neutrons of any energy, low energy neutrons being the most effective. Fission in ^{238}U, which comprises 99.285 percent of natural uranium, can only be caused by neutrons of energy greater than 1MeV.

There are three other isotopes of importance which can undergo fission. ^{232}Th, the only naturally occurring isotope of that element, is fissionable with neutrons with energy greater than about 1.4 MeV, and two isotopes, ^{233}U and ^{239}Pu, which do not occur naturally but can be produced artificially by nuclear reactions, undergo fission with neutrons of all energy, low energy neutrons being again the most effective. It is customary to refer to the five isotopes mentioned above (and any other isotopes which undergo fission with neutrons of energy less than about 10MeV) as fissionable, and to reserve the term fissile for the three isotopes ^{233}U, ^{235}U and ^{239}Pu which undergo fission with low energy neutrons.

The characteristics of fission will be described by considering ^{235}U, however the fission of the other four isotopes is essentially the same in all respects. The first stage of the reaction is the absorption of a neutron in ^{235}U to form ^{236}U at an excited state. In some cases the ^{236}U goes to its ground state of energy by the emission of gamma radiation, an example of an(n, γ)reaction, however in the majority of cases the ^{236}U nucleus splits as described above. The products of fission are two fission fragments whose mass numbers vary between 70 and 160, a number of neutrons varying between none and five, beta particles, gamma radiation, neutrinos and energy. These products are shown diagrammatically in Fig.1.3.

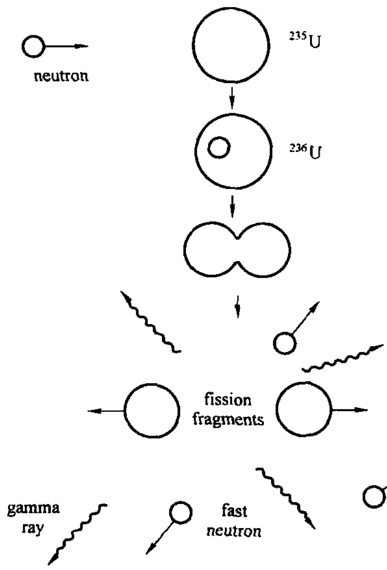

Fig.1.3 The fission process

The release of energy in the fission process may be illustrated by considering the fission of a ^{235}U atom, which splits up into barium and krypton atoms and releases three more neutrons:

$$^{235}U + n \rightarrow {}^{141}Ba + {}^{92}Kr + 3n$$

If we could weigh components in this reaction we would find that those on the right-hand side of the equation weighed 0.091% less than those on the left-hand side. Thus, during the reaction, approximately 0.1% of the original mass is converted into energy. This energy appears as kinetic energy of the fission products and neutrons, which then collide with surrounding atoms and increase their thermal vibration that is, release heat. For each kilogram of ^{238}U totally fissioned by the above reaction, 80 million (8×10^{13}) joules are released. This is equivalent to the energy available from 3000 tons of coal.

^{235}U is described as a *fissile* isotope; unfortunately, naturally occurring uranium consists mainly (99.3%) of a *nonfissile* isotope, ^{238}U. Thus, only a small part of natural uranium can be burned in the fission process to produce energy. The proportion of ^{235}U in natural uranium is 0.71% by weight, and thus 1kg of natural uranium is equivalent in energy potential to about 20 tons of coal. However the energy potential of uranium can be increased about 100-fold by conversion of the nonfissile ^{238}U into another fissile material, namely, plutonium-239(^{239}Pu). We shall return to this below.

The three neutrons emitted in the above fission reaction have an initial velocity of typically 20 000km/s (about 6% of the velocity of light). Although these fast neutrons can interact with other atoms of ^{235}U, their chance of doing so can be increased by about 1000-fold if their velocity can be reduced, say, to 2km/s.[4] These slower-moving neutrons would have a velocity similar to that of atoms vibrating due to thermal motions, and hence they are often called *thermal neutrons*. Nuclear reactors using the fast neutrons are often termed *fast reactors*, and those using the slower neutrons are termed *thermal reactors*.

Fast neurons are converted into thermal neutrons as a result of a series of collisions with surrounding atoms. If a fast neutron hits a large atom, it tends to bounce off and lose only a small amount of its energy. However, if it hits a small atom such as hydrogen or carbon, it will lose a significant fraction of its kinetic energy. (An analogy may be made to the motion of balls on a billiard table. If a ball hits the massive cushion of the table, it bounces off with very little loss of velocity, or kinetic energy. If it hits a stationary ball, it may lose a large proportion of its kinetic energy, which is transferred to the other ball in the collision.) Thus, to convert a fast neutron to a slow or thermal neutron requires about 2000 successive collisions with uranium atoms but only about 20 collisions with the lightest atom, hydrogen. In the collision process, the neutrons are sometimes absorbed without leading to a subsequent fission. Moreover, each successive collision may lead either to a fission reaction or to the neutron's combining with the atom with which it is colliding to make another isotope. Thus, there is an advantage in surrounding the uranium with lighter material that can lead to the conversion of fast neutrons to thermal neutrons, which can then pass back into the uranium this process is known as moderation, and the light material used is termed a moderator. Moderators used in thermal reactors have included hydrogen (in the form of its oxide, water), the hydrogen isotope deuterium(also in the form of its oxide, heavy water) and carbon (usually in the form of graphite). The best moderator is heavy water, which absorbs neutrons only weakly. However, heavy water is an expensive material and it is often preferable to use ordinary (light) water even though it absorbs neutrons much more strongly.

Because ^{238}U absorbs neutrons, it is not possible to produce a self-sustaining chain reaction by simply assembling a large enough mass of natural uranium, which is 99.3% of ^{238}U. However, if pieces of natural uranium are distributed within heavy water or graphite, the neutrons produced in the fission reaction are converted to thermal neutrons(which, as mentioned above, are 1000 times more effective than fast neutrons in continuing the chain reaction), and a self-sustaining chain reaction is possible. This idea was first demonstrated by Enrico Fermi at Stagg Field, Chicago, on December 2, 1942; Fermi employed pieces of uranium distributed in a "pile" of graphite. Light water cannot be used to sustain a chain reaction with natural uranium because of the high absorption of neutrons by hydrogen. However nuclear reactors may be constructed with light water as a kind of moderator provided the concentration of ^{235}U is increased from 0.71% to about 3%.

As we shall see later, various generic types of nuclear reactors have arisen from the various possible combinations of fuel and moderator. These can be classified as follows.

(1) Heavy water-moderated, heavy water-cooled reactors. These are the basis of the Canadian line of development and are called CANDU reactors.

(2) Graphite-moderated, gas-cooled natural uranium reactors. These are the basis of the

British Magnox reactors.

(3) Light water-moderated, light water-cooled reactors with fuel enriched in ^{235}U. These are the basis of the U.S. boiling-water reactor (BWR) and pressurized-water reactor (PWR) development.

The further development of the British system, the advanced gas-cooled reactor(AGR), uses graphite as a moderator and a somewhat enriched fuel to compensate for the fact that the fuel is contained in stainless steel, which absorbs a significant fraction of the neutrons.

We shall describe and discuss all the above reactors, and in particular their cooling problems, in the following chapters. However, before doing so, it may be interesting to glance back to prehistoric times. The light water-cooled and moderated reactors have been around far longer than one might imagine. In fact, the invention of Enrico Fermi was preempted by nature approximately 2 billion years earlier. In 1972, evidence was found of the dormant remains of a natural fission reactor located at Oklo, in the West African Republic of Gabon. This natural reactor operated for a period of hundreds of thousands of years. Its existence was discovered by an intriguing piece of detective work by French nuclear scientists.

In May 1972, H. Bouzigues obtained a curious result during a routine analysis of standard samples of uranium ore from Gabon. He found that they contained about 0.4% less ^{235}U than expected. This was not due to an error in his analysis or to a natural variation. On this planet, at any particular time, the ratio of ^{235}U to ^{238}U is fixed; some other explanation had to be found for the discrepancy. A careful investigation carried out by the French Atomic Energy Agency traced the abnormal ore to one particular location in Oklo. It was concluded that the deficiency in ^{235}U could be explained only by the occurrence of a natural fission reaction at the site. At the time this natural reactor was operating, the ore was buried deep underground and natural groundwater served as a moderator and to some extent as a coolant. Such a reactor would not be possible with the present-day concentration of ^{235}U in naturally occurring uranium, as we explained above. However, it should be remembered that the half-life of ^{235}U is about 700 million years and that of ^{238}U is about 4.5 billion years. Thus, in prehistoric times, the concentration of ^{235}U was much higher than it is today. When the earth was formed some 4.6 billion years ago, the concentration of ^{235}U in natural uranium was about 25%, and it had decreased to about 3% at the time when the Oklo reactor was operating.

It is thought that the natural reactor at Oklo operated under considerable pressure and temperature and that the rate of reaction was controlled by variations of the water (moderator) density. Cooling was provided mainly by conduction, with some limited circulation by permeation. The power level is estimated to have been somewhat less than 100 kW and the total energy released over the period of operation to have been about 4.7×10^{17} joules (15 000 MW-years) , representing the fission of about 6 metric tons of ^{235}U. This amount of energy is about that released in a modern pressurized-water reactor in 4 years.

It is possible that a combination of local circumstances may have led to other naturally occurring reactors. Though the search continues, none has been located so far. Such naturally