



“十二五”普通高等教育本科国家级规划教材

HEDIAN ZHUANYE YINGYU

核电专业英语

(第二版)

阎昌琪 编



中国电力出版社
CHINA ELECTRIC POWER PRESS



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阮於珍 主审



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内 容 提 要

本书为“十二五”普通高等教育本科国家级规划教材。

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

核工程与核技术专业是我国拥有核专业的大学设置的主要本科专业，核电技术是核工程专业的主要专业课程内容，核电所涉及的学科领域广泛，包含很多当今世界的高新技术。美、英等发达国家在该领域处于领先地位，很多核电技术新的研究成果和新技术的介绍都以英文发表，学生毕业参加工作后都要阅读大量的英文资料，为此我们编写了这本核电专业英语教材，供核工程专业本科生提高专业英语阅读能力所用。

本书内容涵盖了核工程类专业所涉及的主要学科，既有与核反应堆有关的基础知识，也有核电站动力系统及主要设备的内容，还包括了核安全的基本常识介绍。书中内容选自英文原版教材和设计说明书，保证了语言的纯正性，同时兼顾内容新、知识面宽；力求课文内容概念性和知识性强、难度适中，不涉及复杂的专业理论。本书的内容安排由浅入深、由基础到专业，每一课都相对独立，可以根据学生的兴趣和专业方向选择使用。

本书第一版自出版以来，受到使用单位比较好的评价，目前几个有核工程类专业的学校都在使用本书作为本科生教材，如西安交通大学、哈尔滨工程大学、华北电力大学等学校都在使用，使用效果良好。同样，由于本书与核电技术紧密结合，目前一些核电人员培训单位已把本书列为岗前培训和订单培养的授课教材，因此本书在核电人才培养方面发挥了比较好的作用。

在本书的教学使用过程中，一些老师和同学都提出了宝贵的意见，对此作者在本次再版时进行了认真修改，在此向在本书编写和校对过程给予帮助的老师 and 同学一并表示感谢。

编 者

2016年6月

第一版前言

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

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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.

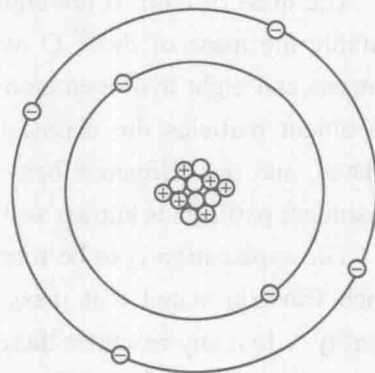


Fig.1.1 atomic structure of carbon 12

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 lies¹.

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 ${}^{16}_8\text{O}$ identifies the isotope of oxygen that has eight protons and eight neutrons in its nucleus. The isotope ${}^{17}_8\text{O}$ has eight protons and nine neutrons in its nucleus. Naturally occurring oxygen consists of a mixture of three isotopes, ${}^{16}_8\text{O}$, ${}^{17}_8\text{O}$ and ${}^{18}_8\text{O}$. 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 ${}^{16}\text{O}$, ${}^{17}\text{O}$ and ${}^{18}\text{O}$.

Hydrogen is an important element in nuclear engineering. Naturally occurring hydrogen consists of two isotopes, 99.985 percent of the isotope ${}^1\text{H}$ and 0.015 percent of the isotope ${}^2\text{H}$ called heavy hydrogen or deuterium. There is a third isotope ${}^3\text{H}$ 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 ${}^{16}\text{O}$ 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 quantity². 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, $2.998 \times 10^8 \text{ m/s}$.

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 $B = \text{total mass of separate particles} - \text{mass of the atom}$ 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 $1\text{u}=931\text{MeV}$, the binding energy is $B=8.48\text{MeV}$.

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.

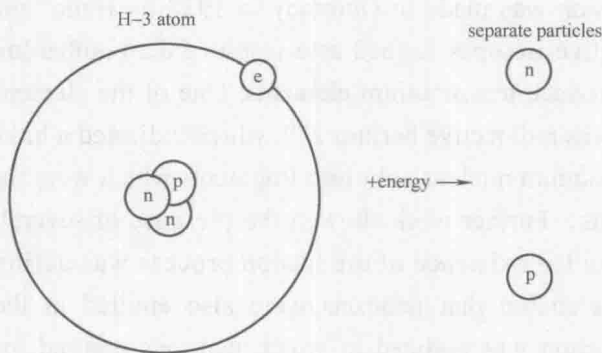


Fig.1.2 dissociation of tritium

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 Hahn³ 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 1 MeV.

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 in Fig.1.3.

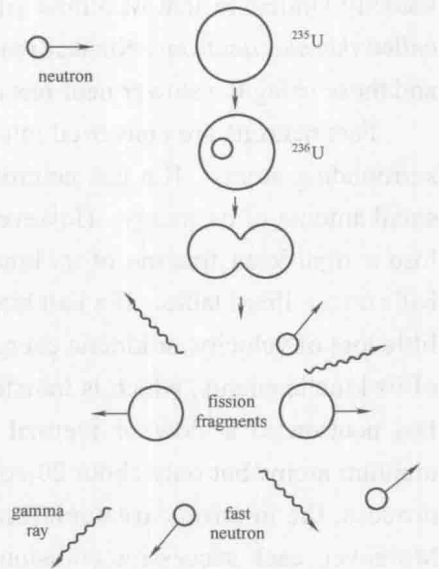
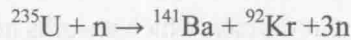


Fig.1.3 The fission process

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:



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 ^{235}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 non-fissile 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 non-fissile ^{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 neutrons 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