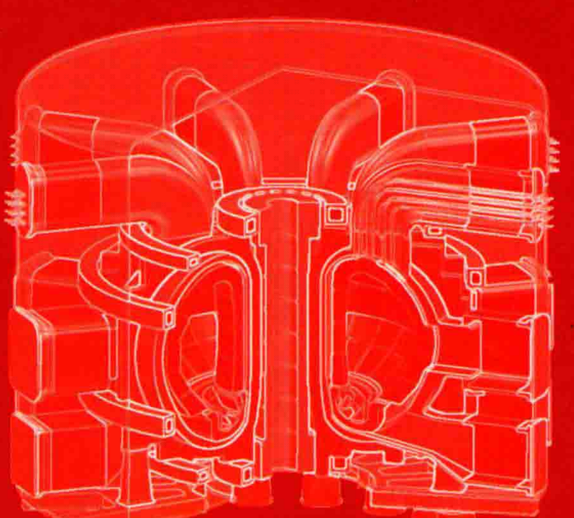
吴宜灿　著

聚变中子学



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Foreword

I am pleased that Prof. Yican Wu has written this excellent book on "Fusion Neutronics". As someone who spent most of his professional career on fusion research and development, including fusion neutronics, I know that there is a great need for such book.

Fusion is known as the ultimate energy source for humanity. If we succeed in developing practical and economical fusion energy system, we would have solved three of the most important challenges humanity facing in the 21st century and beyond: water, energy, and the environment. These three issues are strongly interrelated. The water problem can be solved if we have enough energy for desalination. The quality of the environment can be vastly improved if we develop energy sources to produce energy in an environmentally-responsible manner. Fusion energy systems would provide a universally available, essentially inexhaustible, efficient fuel resource; an energy source to meet growing global energy demand with attractive safety and environmental characteristics. In addition, fusion R&D has and will continue to spawn new technologies for a variety of applications.

Fusion is the energy-producing process taking place in the core of the sun and stars. Fusion research is akin to "creating a star on earth". In fusion, two light nuclei combine to form a heavier nucleus, converting mass to energy — the opposite of nuclear fission where heavy nuclei split. In this nuclear process, a small amount of fuel mass is converted to large amount of energy in contrast to fossil fuels (oil, gas, coal) where chemical energy is stored, and huge mass is needed to "store" energy. The World Fusion Program is currently focused on the Deuterium (D) — Tritium (T) Cycle. In this fuel cycle, a mixture of D and T is heated to 100 million degrees, which is 10 times hotter than the temperature inside the sun, to form plasma. Under such high temperature, D and T can fuse and release 17.58 MeV in energy with a 14.06 MeV neutron and 3.52 MeV alpha (helium) particle.

The energetic 14.06 MeV neutron carries 80% of the fusion energy release. This energy must be deposited in the region surrounding the plasma, called blanket. Deuterium is abundant in nature but tritium is not and must be generated, "bred", in the blanket via tritium-producing neutron interactions with lithium. Hence, neutrons play the major role in energy conversion and tritium fuel breeding in fusion energy systems. Therefore, it is essential to predict precisely neutron transport and interactions with all materials surrounding the plasma. In addition to nuclear heat generation and tritium breeding, neutron interactions with materials produce atomic displacements and gases such as helium and hydrogen that must be calculated precisely as input to evaluating radiation damage to materials. Neutrons interactions with materials also result in induced radioactivity, and decay heat that must be calculated accurately. The field of fusion neutronics is concerned with predicting the transport of neutrons and associated secondary gamma rays and calculating the nuclear responses resulting from neutron interactions with matters such as tritium breeding, nuclear heating, induced radioactivity, atomic displacements, gas production, and many other responses. In addition to transport simulation and nuclear responses calculation, fusion neutronics also involves experiments ranging from basic data measurements, to benchmark experiments, and carefully designed integral experiments in which the key features of the fusion system configuration and materials are simulated.

The presence of the 14.06 MeV neutrons with much higher energy than neutrons in fission reactors required that major advances be made in order to develop the field of fusion neutronics. At such high energy, many reactions are accessible, and the anisotropy in neutron interactions is strong and cannot be neglected. In addition, the fusion energy system has many components with complex configuration and geometry. Therefore advances needed to be made in nuclear data measurements, nuclear data processing, development of 3-D transport codes that can handle deep radiation penetration and details of multi-region and complex geometry.

These advances have been made over the past 40 years. These are documented in a large number of papers in scholarly journals and proceedings of conferences. But until now, there has been no book written about fusion neutronics despite the clear need for such book. Therefore, I applaud the efforts of Prof. Yican Wu in writing this book on Fusion Neutronics. It is much needed and it will be of great value for the education of students and as a reference for experts. The book covers all key topics in fusion neutronics from fundamental principles to description of the state-of-the-art methods, codes, and data libraries as well as wide range of applications, deign, and analysis.

The author, Prof. Yican Wu, is a world recognized leader in advanced nuclear system research, especially in neutronics. He is an expert on fusion neutronics who together with his team made important contributions to advancing the field of fusion neutronics. They have made important advances in developing methods and codes such as the development of the computer code SuperMC, which is now being used in many institutions around the world. They competently applied fusion neutronics codes and data libraries to the design of a wide range of conceptual reactor deigns and the planning of important nuclear facilities. Prof. Yican Wu's deep knowledge and experience in fusion neutronics combined with his remarkable skills in teaching and training of students and young scientists enabled him to write this book. It is a comprehensive and clear book on fusion neutronics, which opens this field to new horizons, and will be certainly a continuous source of innovative ideas to promote the neutronics research of fusion and other advanced nuclear energy. I strongly recommend this book to students as well as experts in fusion who need a good, reliable reference.

Mohamed Abdou
Distinguished Professor of Engineering and Applied Science
Director of Fusion Science and Technology Center
University of California-Los Angeles

Foreword

Fusion energy is regarded as the ultimate energy source for human beings in the long run. The first large-scale release of fusion energy on earth was in the form of hydrogen bomb in the early 1950s. Since then, great progress has been achieved aiming to produce fusion energy in a controlled manner with the construction and experiments of numerous facilities such as TFTR, JET, JT-60U, DIII-D, ASDEX-Upgrade, etc. However, the early study of fusion energy has been focused on the "plasma physics" to solve the problem of confining plasma. Before the commercial application of fusion energy, there are still many physical and technological problems to be solved, for which one of the most important issues is the usage and protection of fusion neutrons.

The neutron is not only the main energy carrier but also the basic cause of nuclear problems in fusion facilities. The introduction of fusion neutrons will bring benefits such as tritium production and energy production, along with problems such as radioactive waste, occupational radiation exposure, radiation environmental impact, etc. Fusion neutronics involves the research of basic neutronics theories, numerical simulation methodologies, engineering designs and experimental techniques, and it is focused on pursuing the best way to increase the neutrons production, improve the electricity conversion efficiency of neutron energy, and to ensure radiation safety with the best effective protection from neutrons.

I have known Prof. Yican Wu for more than 10 years and closely collaborated in a series of ITER neutronics related works. I am very impressed by his unceasing passion, creativity and diligence. He is one of the top-level scientists in research and development of advanced nuclear systems, and has been devoted to neutronics research for more than 30 years. He and his team have made great contributions in neutronics related research, and have become one of the leading teams in this area in the world. For example, he has made great efforts to solve the neutron transport problems in large scale and complex systems, and has developed an excellent nuclear analysis software system named SuperMC, which firstly presents innovative ideas on automatic and accurate modeling, and integrates automatic modeling, coupled calculation, cloud computing, visualized analysis and simulation. The software greatly speeds up the neutronics analyses and was selected as the reference for ITER neutronics modelling. Using this excellent SuperMC program, a series of very detailed and accurate nuclear analysis models of ITER tokamak and components, including the ITER 3D basic neutronics models, has been created, allowing accurate nuclear analysis for many components. Investigations such as the heating of TF coils, included as a crucial neutronics issue by the Science and Technology Advisory Committee of ITER Council, led to several shielding improvements to the ITER machine.

Those creative achievements made by Prof. Wu and his team have represented a major contribution to the progress in recent years in the field of neutronics and greatly promoted the development of the research areas. His outstanding achievements and insights make the advent of this profound book a reality. It is the first specialized book on fusion neutronics that provides a systematic and comprehensive introduction of the field, summarizing not only the results of the Prof. Wu's work, but also an excellent survey on the state of the art of neutronics.

As someone who has already worked in this area for many years, I strongly recommend this pioneering book to experts and students, and sincerely wish that it will be of practical use to a large number of general readers. I believe it will stimulate and promote further research in the field.

Michael Loughlin
Neutronics & Nuclear Analysis Coordinator
The ITER Organization

前　言

聚变能是一种潜在的用之不竭的清洁能源，而氘氚聚变是目前公认的最有希望实现聚变能应用的途径，中子作为系统中氘氚聚变能量转换和氚燃料自持的重要媒介，被视为聚变系统的“灵魂”。聚变中子学是一门围绕聚变中子的产生、利用和防护开展研究的新兴交叉学科，内容涉及描述中子行为的基础理论与方法、中子利用和防护相关的系统设计与技术。聚变中子学研究方兴未艾，国内外尚无系统论述其内容体系的专业著作，给从事聚变能基础理论研究、聚变堆设计和技术开发的学者们带来不便。

作者及其研究团队自20世纪80年代以来持续从事聚变中子学相关研究。本书基于作者及其团队多年来的研究成果，从中子学基础理论、方法、实验以及聚变系统设计原理等方面阐述聚变中子学的研究内容。全书分为三篇，共13章：上篇从中子输运理论出发，结合中子对聚变系统、环境及生物的作用原理展开全面介绍，落脚于中子行为的综合模拟技术；中篇针对聚变系统的中子学特点和设计要求，以国际热核实验堆、聚变动力堆和聚变裂变混合能源系统为例，介绍其中子学设计原理，阐述中子学理论与方法在工程实践中的应用；下篇介绍聚变中子学的实验技术和典型实验装置，并对中子学实验的研究现状和发展趋势进行了总结与探讨。

本书撰写过程中，作者力求结构层次分明、内容全面系统，以便于广大聚变能研究人员及感兴趣的学者们学习、参考。聚变中子学是一门正在发展中的学科，有许多问题待进一步探索，书中难免存在不足之处，真诚希望读者不吝指正，提出宝贵意见。

谨以此书纪念中国科学院核能安全技术研究所成立五周年。

吴宜灿

目　　录

中篇 聚变中子学设计原理

第1章 绪 论

能源是社会和经济发展的基础，是人类生活和生产不可缺少的资源。随着社会的发展，能源的需求也在不断扩大。目前世界上使用的煤、石油和天然气等化石能源储量正日趋减少，且会对生态环境造成污染。为了缓解能源与环境的矛盾，世界各国正在积极开发太阳能、风能、潮汐能和生物质能等可再生能源。然而，可再生能源能量密度低，受自然条件影响大，实现大规模稳定应用难度高。核能仍是目前公认可大规模替代化石能源的清洁经济能源。

核能根据核反应类型的不同可分为两类：核裂变能与核聚变能。目前正在运行的核电厂是核裂变电厂，其发展主要面临放射性安全（如三哩岛、切尔诺贝利和福岛核电厂发生的核事故）、核废物累积（放射性毒性大且潜在危害可持续百万年）和核燃料有限（仅可供现有反应堆使用数十年）三大问题。而核聚变能具有“清洁、安全、永久”的特点，因此被作为战略能源发展，备受关注。

与传统核系统相比，聚变系统（包括聚变实验堆、聚变动力堆、聚变裂变混合堆和聚变中子源等）具有许多不同的特点，如中子能量高（14.06 MeV）、能谱范围宽且复杂、中子散射各向异性强烈、材料组成复杂且分布不均匀、系统尺寸庞大且结构复杂等，给中子学研究带来许多新的问题，因此有必要开展聚变中子学专门研究。本章介绍聚变中子产生原理、聚变反应装置、聚变能发展技术路线，并对聚变中子学学科进行概述。

1.1 聚变中子的产生

1919 年，英国物理学家阿斯顿（F. Aston）发现轻核聚变反应。1934 年，澳大利亚物理学家奥利芬特（M. Oliphant）用氘（D）轰击氘，生成一种具有放射性的氢同位素氚（T），首次实现氘氘（D-D）核聚变反应。实验发现很多轻核聚变反应都能放出能量，其中具有代表性的聚变反应为：

$$^{2}D+^{2}D\rightarrow ^{3}He(0.82\ MeV)+n(2.45\ MeV) \tag{1-1}$$

$$^{2}D+^{2}D\rightarrow ^{3}T(1.01\ MeV)+p(3.02\ MeV) \tag{1-2}$$

$$^{2}D+^{3}T\rightarrow ^{4}He(3.52\ MeV)+n(14.06\ MeV) \tag{1-3}$$

$$^{2}D+^{3}He\rightarrow ^{4}He(3.67\ MeV)+p(14.67\ MeV) \tag{1-4}$$

由聚变反应产生的中子称为聚变中子。上述四种反应中，75％～80％的聚变能都由反应产生的中子或质子携带，其中反应(1-1)与反应(1-3)分别会产生能量为2.45 MeV和14.06 MeV的中子。聚变反应的截面与氘离子能量的关系(数据出自ENDF/B-Ⅷ.1)如图1-1所示。从图1-1中可以看出在几种聚变反应中氘氚(D-T)反应截面最大，最容易实现。因此，尽管面临着氚供给及高能中子屏蔽等问题，D-T反应仍被认为是未来聚变反应堆的首选反应。本书中所述的聚变反应与聚变中子将特指D-T反应及其产生的14.06 MeV中子。

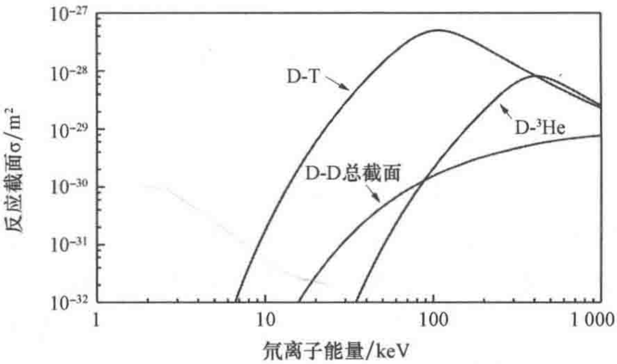

图1-1 聚变反应截面随粒子动能的变化

聚变能是指利用氘、氚等轻核聚变反应释放的能量，相比于裂变能，聚变能具有富中子、贫能量(17.58 MeV/次)的特点，其优点主要体现在以下三个方面：

(1) 聚变燃料丰富

氘和氚是聚变堆的主要燃料，地球上的氘储量极其丰富，每1 L海水中约含有33 mg氘，海水中总计含有4.5×10^{13} t氘，如果全部提取用于聚变反应堆燃烧，参照2015年全球发电总量23 111.37 TWh计算，可供人类使用上千亿年。氚在自然界中几乎不存在，在聚变堆中可以通过中子与包层中锂原子发生吸收反应生产氚。锂在地球上储量比较丰富，海水中锂储量约有2.6×10^{11} t，如果全部提取用于聚变反应堆燃烧，足够人类使用上千万年。

(2) 无长寿命高放核废物，放射性危害小

氘氚聚变主要产物为惰性气体氦。聚变堆退役时的放射性废物主要来自氚化物和高通量聚变中子辐照下结构材料、增殖剂、冷却剂等的活化产物。按照国际原子能机构(International Atomic Energy Agency，IAEA)放射性物质分类方式，聚变堆产生的放射性废物多为低放和中放核废物，几乎不产生目前无法有效处理的长寿命高放核废物。

此外，作为聚变燃料的氚，半衰期相对较短($T_{1/2}\approx12.31$ a)，且β衰变释放的电子能量低(平均5.68 keV)，基本不会造成人员外照射损伤，即使发生泄漏事故，