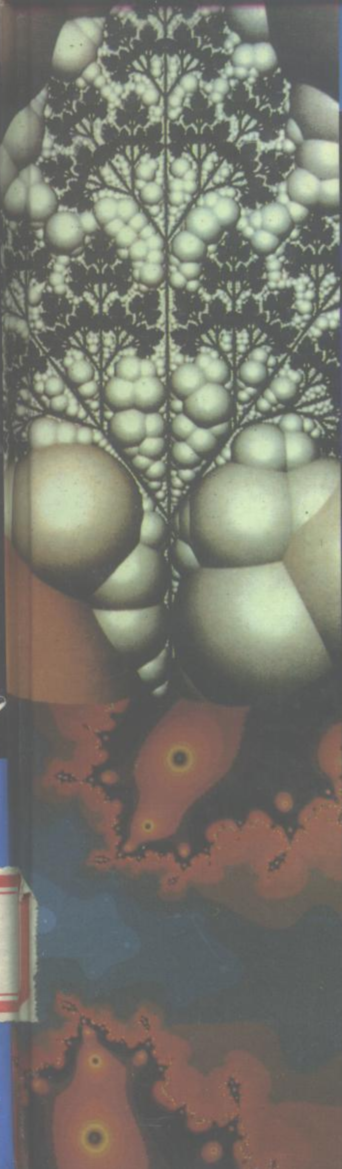
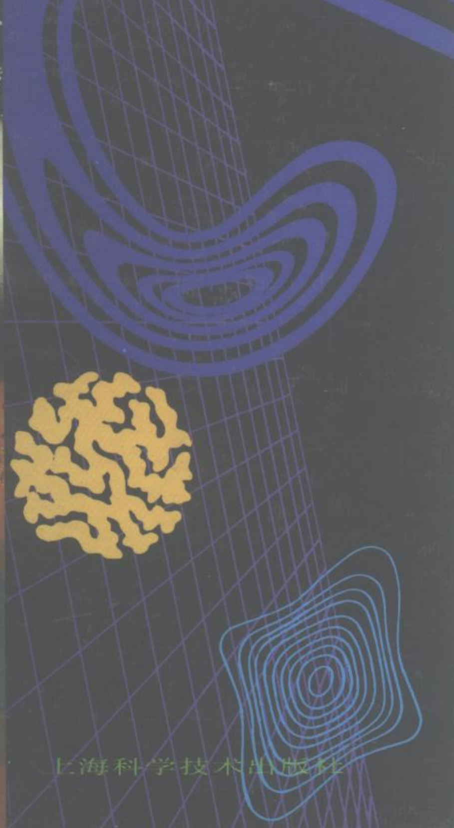
物理学前沿丛书



量子
混沌运动

徐躬耦　著



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A FRONTIER SERIES IN PHYSICS

CHAOTIC MOTIONS IN QUANTUM SYSTEMS

Xu Gongou

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内容提要

本书对量子系统混沌运动的现状和最新发展作了分析和论述。全书共九章，分别阐述经典哈密顿系统的混沌运动、量子混沌运动研究的现状、量子混沌研究中必须澄清的一些基本概念、量子正则变换与量子系统的可积性、准定态过程中量子正则变换的破折、达到混沌状态时的统计性质和相应的关于能谱涨落的统计理论、非定态过程中量子正则变换的破折和达到混沌状态时的统计性质、量子系统的状态趋向混沌的演化过程，以及有待讨论的一些问题。全书反映作者及其研究组的研究成果，该研究课题是国家基础性研究《攀登计划》的重点项目。

本书适合理论物理学及相关学科的研究工作者和高等院校师生阅读。

A FRONTIER SERIES IN PHYSICS

EDITORIAL BOARD

出版说明

我社在物理学界专家学者的热忱关怀下，历年来出了一些比较好的书，如《晶体生长的物理基础》(闵乃本著)、《原子物理学》(第一版杨福家著)、《原子结构核理论》(曾谨言、孙洪州编著)、《群表示论的新途径》(陈金全著)、《物理学中的群论》(陶瑞宝著)、《近代物理学》(倪光炯、李洪芳编著)，等等。这些书受到国内外物理学界、出版界和读者的欢迎和好评。为进一步出好这方面的著作，我社拟出版《物理学前沿丛书》。其宗旨是：向国内外介绍我国第一流的物理研究成果，扩大我国物理研究成果在国内外的影响，促进学科的发展和交流。《物理学前沿丛书》包括的面：基础物理、应用物理和技术物理的前沿领域。

考虑到物理科学的特点，在大体统一的规格要求下，我们将充分发挥作者的特长，努力使本丛书具有丰富多采的风格。例如：(1)作者可以对一个专门分支学科，按自己的观点作比较全面深入的阐述，其中一部分内容反映作者自己的创造性工作；(2)作者也可以为着重反映自己有特色的、比较成熟的系统性研究，就某一个重要的课题作详细的介绍，但应包括必要的预备知识和有关课题在国际上的发展动态；(3)在某一领域或新课题的研究发展特别迅速的情况下，我们也可把系列学术报告或专门性讲座汇编起来，经过适当加工，再加上一个比较详细的前言介绍，以便尽快出版；(4)在考虑书稿时应充分注意历年来“获奖”项目和国家基金会重点资助的项目。

我们希望，本丛书不仅可以作为高年级大学生和研究生的教材，而且对广大的教师和科研工作者有益，经若干年有了适当的积累之后，能够在一定程度上显示出我国物理学界的风貌。

我们诚恳希望得到物理学界广大专家的大力支持和指导，使这套书的出版达到预期的目的。

上海科学技术出版社
1992年10月

序

混沌作为一门新科学而兴起，无疑地将会消除对于统一的自然界的确定论和概率论两大描述体系间的鸿沟。正因为如此，所以有人认为我们正在酝酿20世纪物理学的第三次革命，前两次是相对论和量子力学。如果我们认为Poincaré是这门科学的奠基人，就会感到奇怪为什么它不在前两次革命之先就发生。的确，混沌所涉及的是一些非常基本的内容。尤其是关于两个自由度的一些讨论，按理说，应是经典力学或量子力学教科书的基本内容。一个人如果没有形成“所有动力系统都是可积的，问题只是在找出合适的正则变换”这样一种印象，就可能想到其中的有关问题。然而关于混沌的观念又是那样艰涩，要让未接触过混沌的物理学同行接受经典混沌的观念不是一件很容易的事，至于要弄清楚量子混沌中的一些观念，那就更加困难得多。就是直接从事量子混沌工作的人，对一些问题也存在着不同的甚至相反的见解。有人认为由于量子系统具有不确定性，并不存在经典混沌那样的确定论性的量子混沌。因此，量子混沌也许应称为发展初的科学。

扼要地讲，经典系统的确定论性的混沌，就在于研究相空间中相点的轨迹对于初条件的微小改变的不稳定性。两个初条件相近的轨迹彼此偏离的程度将随着时间按指数地增长。那末量子系统的混沌运动又怎样呢？量子力学是为了阐明微观粒子的运动而建立起来的。经典力学的研究对象则是这些微观粒子所组成的宏观物体。经典力学，包括经典混沌，应是量子力学在极限条件下的表现。但也许是由于量子力学的辉煌成就，使得人们顾不上这方面的工作。因而量子力学的极限过渡问题，一直没有真正严格地实现。

最近十多年来，在经典混沌成就的推动下兴起的量子混沌研究，正是朝着这一方向而作的努力。通常采用的途径是寻找其经典对应显示出混沌运动的量子系统的运动的类属表现。从数值解给出了能谱或准能谱的涨落的统计规律性、波包的不稳定性、以及与局域化连系着的量子抑制等等。但这些饶有兴趣的数值结果的动力学根源一直没有弄清楚。早期，人们主要从经典系统出发去考虑量子经典对应问题。例如，显示出混沌运动的经典系统的量子化问题，爱因斯坦1917年时就已提出，但一直未能解决。近年来，也有另一些工作，企图直接从量子力学出发，去考察量子经典对应，虽是初步的，但很值得注意。可以说，量子混沌的研究显示出了一种风格纷呈、百花齐放的局面。

量子混沌研究的这种状况，也反映在已出版的涉及量子混沌的著作和已发表的评述性论文中。有的对量子混沌或其某个方面的大量工作做了比较全面的介绍。这种形式对初学者似乎并不相宜，往往乍读之下，有一种茫茫然不知所从的感觉。有的是对于某个专题的论述，这种形式自然更适宜于专门工作者。近年出版的Gutzwiller的著作强调概念和实例，着眼于经典力学和量子力学间的连系来讨论，对量子力学中是否存在确定论性的混沌则持开放态度。此书出版以后，较受读者欢迎。现在再能为读者增添什么样的量子混沌的参考书呢？我们势必采取另一种选择。

作者只想根据自己近年来的研究工作（研究课题曾得到国家自然科学基金及国家基础性研究《攀登计划》《非线性科学》项目资助），以量子经典对应原理为指引，讨论量子混沌的基本问题。不同于目前其他著作者，本书采用一步一步地比较系统的方式来进行讨论，从运动学到动力学，从规则运动到混沌运动，都是既注意量子经典对应，又始终以量子力学自身框架为基点来讨论，我们并不认为已经作出了定论，而是想抛砖引玉，起到促进讨论、促进发展的作用。

本书的内容是这样组织的：第一章对经典混沌运动作了简单介绍，第二章对量子系统混沌运动研究的现状作了粗浅分析，第三

章对量子混沌运动研究中的一些观念作了原则性讨论。这三章具有导论性质。对于第三章的内容，初次阅读时，只需要有一个大致的理解，读过有关章节后还可以返回来再读。第四章论述量子正则变换的性质以及它作为量子规则运动的充要条件，是后面各章的基础。在此基础上首先讨论准定态过程中量子正则变换的破折(第五章)；和达到混沌状态时的统计性质以及相应的能谱涨落的统计理论(第六章)；再进一步扩展到一般的非定态过程，讨论量子正则变换的破折和达到混沌时的统计性质(第七章)，以及通向统计平衡的弛豫过程的理论(第八章)。最后在第九章中简略谈了谈尚待讨论的问题。

正如前面指出的，这些都是非常基本的内容，需要的准备知识只是经典力学(含分析力学)和量子力学。另外还要有一些与动力群的可互易量完备集(CSCO)有关的群论知识。本书可供物理学工作者及物理系研究生或高年级本科生参考。

本书的写成得益于作者负责的课题组近年来的工作进展。参加课题组工作的有杨亚天、傅德基、王文阁、揭泉林、龚江滨等，任中洲、王荣平、王能平等也参加过一些工作。作者感谢倪光炯、顾雁、卓益忠、王顺金、冯达旋教授等在本书完成过程中所给予的帮助。由于作者学识所限，本书肯定存在许多不妥之处，尚祈各方专家学者和广大读者予以指正。

徐躬耦

1993年8月

Preface

Chaos which comes into being as a new branch of science will undoubfedly fill the gap between the radically different deterministic and probabilistic descriptions of the unified nature. Because of this, someone think we are in the eve of the third revolution of physics of the twentieth century, the previous two are the theory of relativity and quantum mechanics. If we consider Poincaré as the founder of this branch of science, one will wonder why it did not come before the previous two. Indeed subject matters involved in chaos are just fundamental ones. Especially for a system with only two degrees of freedom, they are just essential contents of textbooks of classical and quantum mechanics. If one is free from such false impression that all dynamical systems are integrable and only required to find the proper canonical transformations, he might be aware of the involved questions. However, the concepts of chaos are rather unfamiliar or even in conflict with one's previous knowledge, it is not easy for a physist to accept fully the concepts of classical chaos at the first time, and would be much more difficult to accept the concepts of quantum chaos. There exist different, even opposite opinions among the physists working on quantum chaos. Someone think that quantum systems cannot have deterministic chaos in the same spirit as for classical systems owing to the uncertainty principle. Therefore quantum chaos may be reasonably regarded as developing science at its early stage.

Briefly speaking, the deterministic chaos of classical systems is characterized by the instability of trajectories of phase points in phase space to slight change of initial conditions, the deviation of two neighbouring trajectories increases exponentially with time. Then what will be the case for chaotic motions of quantum systems? Quantum mechanics is established to describe motions of microscopic particles, while classical mechanics describes the motion of a macroscopic body consisting of microscopic particles. Therefore classical mechanics including classical chaos should result from quantum mechanics in limiting conditions. It is perhaps owing to the glorying success of quantum mechanics, this kind of work escapes from one's notice. The classical transition of quantum mechanics in limiting conditions is not yet fully realized.

In recent years, with the success of classical chaos, the study of quantum chaos develops rapidly aiming at that goal. The most popular way is to look for generic chaotic behaviors of quantum systems of which the corresponding classical systems show chaotic behaviors. The numerical results obtained show that fluctuations of energy and quasi-energy spectra indeed obey the statistical law. Other results give some indications to instability of wave packets and also quantum suppression associated with the localization. But the dynamical origin of these interesting results is still unclear. In early days the quantum-classical correspondence was studied by starting from classical systems, the quantization of classical systems showing chaotic motions has been raised by Einstein at 1917. But this problem is still unsolved. Recently there appear works studying the quantum-classical correspondence by starting from quantum systems, this seems to be the more powerful direction. It is reasonable to say the current situation of the study of quantum chaos is full of various styles in the same manner as the garden is full of different kinds of blooming flowers.

Such a kind of situation of the study of quantum chaos will of course be reflected in books and review articles of this field. Some of them just gave an overview to the published articles. This style is not so suitable to beginners of this field to them the main object is to obtain quickly a general understanding of the subject. Some of them dealt with a certain topic to some depth, of course this style is more suitable to specialists in this field. The book written by Gutzwiller published in 1990 put emphasis on ideas and examples and singled out the questions that have a bearing on the connection between classical and quantum mechanics. Gutzwiller's book was welcomed by a wide scope of readers. Now what can I add to the list of reference books? I have to take another kind of choice.

To the author's opinion based on his recent works supported by National Natural Science Foundation and National Basic Research Project "Nonlinear Science", it is preferable to study the basic problems of quantum chaos with the guidance of the quantum-classical correspondence principle. Thus, differing from the existant books, I attempt to carry out discussions step by step in a rather systematic way, from kinematics to dynamics, from regular motions to chaotic motions. And the discussions are carried out within the framework of quantum mechanics itself throughout, while at the same time the quantum-classical correspondence is carefully studied at all steps. I dont think the final conclusion of the problem has been reached. I rather consider the publication of the book as a way for facilitating discussions and promoting developments.

The contents of the book is organized as follows. In chapter 1, a brief review is given to classical chaotic motions. In chapter 2, the current situation of the study of quantum chaos is analyzed. In chapter 3, some notions important to the study of quantum chaos are discussed in principle. These three chapters constitute the introductory part of the book. It is only required to have a general idea about the contents of chapter 3 at the first reading, readers may come back to these matter afterwards. In chapter 4, a detailed discussion is made for properties of the quantum canonical transformation and the role as sufficient and necessary condition for quantum regular motions. This chapter serves as the foundation of the following chapters. Based on it, we first discuss the breaking of quantum canonical transformations in quasi-stationary processes (chapter 5), and statistical properties under the condition of quantum chaos together with the statistical theory of fluctuations of energy spectra (chapter 6). Then we go further to discuss the breaking of quantum canonical transformations in nonstationary processes and statistical properties under the condition of quantum chaos (chapter 7), and the statistical theory of the relaxation process leading to statistical equilibrium (chapter 8).

At last a few words are given to some problems to be discussed (chapter 9).

As pointed out previously, the subject matter discussed is quite elementary in character, the prerequisite knowledge needed is just classical mechanics (including analytical mechanics) and quantum mechanics. Besides, it is hoped to have some knowledge of the group theory in connection with the complete set of commuting observables (CSCO) of the dynamical group. This book can be used as a reference book for physists in various fields and also graduate and senior students of physics.

The completion of this book is much benefitted by recent works of my group. Among the collaborators are Yang Yatian, Fu Deji, Wang Wenge, Jie Quanlin and Gong Jiangbin. Ren Zhongzhou, Wang Rongping and Wang Nengping have also taken part in some works. The author should acknowledge professors Ni Guangjiong, Gu Yan, Zhao Yizhong, Wang Shunjin and Feng Dahsuan for their help during the completion of the book. The author would also like to thank the editor Mr. Dai Xuewen for his painstaking work and intelligent collaboration. Due to the limited knowledge of the author, there exist inevitably defects in the book. Critisims from specialists and readers are warmly welcomed.

Xu Gongou

Aug. 1993