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非理想等离子体的量子统计

（影印版）

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序　　言

物理学是研究物质、能量以及它们之间相互作用的科学。她不仅是化学、生命、材料、信息、能源和环境等相关学科的基础，同时还是许多新兴学科和交叉学科的前沿。在科技发展日新月异和国际竞争日趋激烈的今天，物理学不仅囿于基础科学和技术应用研究的范畴，而且在社会发展与人类进步的历史进程中发挥着越来越关键的作用。

我们欣喜地看到，改革开放三十多年来，随着中国政治、经济、教育、文化等领域各项事业的持续稳定发展，我国物理学取得了跨越式的进步，做出了很多为世界瞩目的研究成果。今日的中国物理正在经历一个历史上少有的黄金时代。

在我国物理学科快速发展的背景下，近年来物理学相关书籍也呈现百花齐放的良好态势，在知识传承、学术交流、人才培养等方面发挥着无可替代的作用。从另一方面看，尽管国内各出版社相继推出了一些质量很高的物理教材和图书，但系统总结物理学各门类知识和发展，深入浅出地介绍其与现代科学技术之间的渊源，并针对不同层次的读者提供有价值的教材和研究参考，仍是我国科学传播与出版界面临的一个极富挑战性的课题。

为有力推动我国物理学研究、加快相关学科的建设与发展，特别是展现近年来中国物理学者的研究水平和成果，北京大学出版社在国家出版基金的支持下推出了“中外物理学精品书系”，试图对以上难题进行大胆的尝试和探索。该书系编委会集结了数十位来自内地和香港顶尖高校及科研院所的知名专家学者。他们都是目前该领域十分活跃的专家，确保了整套丛书的权威性和前瞻性。

这套书系内容丰富，涵盖面广，可读性强，其中既有对我国传统物理学发展的梳理和总结，也有对正在蓬勃发展的物理学前沿的全面展示；既引进和介绍了世界物理学研究的发展动态，也面向国际主流领域传播中国物理的优秀专著。可以说，“中外物理学精品书系”力图完整呈现近现代世界和中国物理

科学发展的全貌，是一部目前国内为数不多的兼具学术价值和阅读乐趣的经典物理丛书。

"中外物理学精品书系"另一个突出特点是，在把西方物理的精华要义"请进来"的同时，也将我国近现代物理的优秀成果"送出去"。物理学科在世界范围内的重要性不言而喻，引进和翻译世界物理的经典著作和前沿动态，可以满足当前国内物理教学和科研工作的迫切需求。另一方面，改革开放几十年来，我国的物理学研究取得了长足发展，一大批具有较高学术价值的著作相继问世。这套丛书首次将一些中国物理学者的优秀论著以英文版的形式直接推向国际相关研究的主流领域，使世界对中国物理学的过去和现状有更多的深入了解，不仅充分展示出中国物理学研究和积累的"硬实力"，也向世界主动传播我国科技文化领域不断创新的"软实力"，对全面提升中国科学、教育和文化领域的国际形象起到重要的促进作用。

值得一提的是，"中外物理学精品书系"还对中国近现代物理学科的经典著作进行了全面收录。20世纪以来，中国物理界诞生了很多经典作品，但当时大都分散出版，如今很多代表性的作品已经淹没在浩瀚的图书海洋中，读者们对这些论著也都是"只闻其声，未见其真"。该书系的编者们在这方面下了很大工夫，对中国物理学科不同时期、不同分支的经典著作进行了系统的整理和收录。这项工作具有非常重要的学术意义和社会价值，不仅可以很好地保护和传承我国物理学的经典文献，充分发挥其应有的传世育人的作用，更能使广大物理学人和青年学子切身体会我国物理学研究的发展脉络和优良传统，真正领悟到老一辈科学家严谨求实、追求卓越、博大精深的治学之美。

温家宝总理在2006年中国科学技术大会上指出，"加强基础研究是提升国家创新能力、积累智力资本的重要途径，是我国跻身世界科技强国的必要条件"。中国的发展在于创新，而基础研究正是一切创新的根本和源泉。我相信，这套"中外物理学精品书系"的出版，不仅可以使所有热爱和研究物理学的人们从中获取思维的启迪、智力的挑战和阅读的乐趣，也将进一步推动其他相关基础科学更好更快地发展，为我国今后的科技创新和社会进步做出应有的贡献。

"中外物理学精品书系"编委会 主任

中国科学院院士，北京大学教授

王恩哥

2010年5月于燕园

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Quantum Statistics of Nonideal Plasmas

In Collaboration with T. Bornath

With 141 Figures

Springer

Preface

During the last decade impressive development and significant advance of the physics of nonideal plasmas in astrophysics and in laboratories can be observed, creating new possibilities for experimental research. The enormous progress in laser technology, but also ion beam techniques, has opened new ways for the production and diagnosis of plasmas under extreme conditions, relevant for astrophysics and inertially confined fusion, and for the study of laser-matter interaction. In shock wave experiments, the equation of state and further properties of highly compressed plasmas can be investigated.

This experimental progress has stimulated the further development of the statistical theory of nonideal plasmas. Many new results for thermodynamic and transport properties, for ionization kinetics, dielectric behavior, for the stopping power, laser-matter interaction, and relaxation processes have been achieved in the last decade. In addition to the powerful methods of quantum statistics and the theory of liquids, numerical simulations like path integral Monte Carlo methods and molecular dynamic simulations have been applied.

This situation encourages us to present this new book on the quantum statistical theory of nonideal plasmas. The goal of this book is to present the basic theory of nonideal partially ionized plasmas from a unified point of view of quantum field theoretical methods. This book arose out of lectures given by the authors and out of their extensive experience in the field of quantum statistics and the theory of charged many-particle systems. On the one hand, an introduction is given into the quantum statistics of equilibrium and non-equilibrium systems on the basis of the methods of real-time Green's functions. On the other hand, the dynamical, the thermodynamic and the kinetic properties of strongly coupled plasmas are dealt with on a wide scale.

This book is intended as a graduate-level textbook and as a monograph on quantum statistical theory of charged many-particle systems, especially nonideal plasmas. We hope that it will be also useful to researchers in the field of plasma physics and quantum statistics.

We would like to thank all those who have encouraged and assisted us in this task. First, we are grateful to Günter Ecker for his motivation and help in the realization of this volume. We thank the team at Springer, especially Adelheid Duhm and Claus Ascheron, for their constructive collaboration.

In particular, we are grateful to Thomas Bornath. The parts about two-particle properties, kinetic equations, ionization kinetics, and laser–plasma interaction include many results worked out together with him and were written in fruitful collaboration. Our thanks go also out to Valery Bezkrovniy, Dirk Gericke, and Dirk Semkat for many helpful discussions and for critically reading parts of the manuscript.

This monograph involves many results of the long-time pleasant collaboration with our friends and colleagues Werner Ebeling, Gerd Röpke, Yury Lvovich Klimontovich (†), Klaus Kilimann, Michael Bonitz, Hubertus Stolz (†), Roland Zimmermann, Ronald Redmer, Hugh E. DeWitt, and Piet Schram. Essential results presented here have been obtained and published in cooperation with these colleagues.

Furthermore, we gratefully thank Stefan Arndt, Roman Fehr, Gordon Grubert, Paul Hilse, Hauke Juranek, Ulrike Kraeft, Sylvio Kosse, Sandra Kuhlbrodt, Renate Nareyka, Ralf Prenzel, Jörg Riemann, and Jan Vorberger for their cooperation and assistance in different stages of the genesis of this monograph while preparing the manuscript.

Finally, it is a pleasure to thank many fellow scientists of the plasma community and Green's function specialists including W. Däppen, J. Dufty, V. Filinov, V. Fortov, K. Henneberger, F. Hensel, D.H.H. Hoffmann, M. Knaup, H.S. Köhler, H.J. Kull, H.J. Kunze, N.H. Kwong, P. Lipavský, B. Militzer, K. Morawetz, P. Mulser, M. Murillo, S.V. Peletminski, F.J. Rogers, R. Sauerbrey, V.G. Špička, W. Theobald, C. Toepffer, and G. Zwicknagel for illuminating discussions and collaboration.

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Rostock and Greifswald
December 2004

Dietrich Kremp
Manfred Schlanges
Wolf-Dietrich Kraeft

Table of Contents

1. Introduction

In the process of the formation of matter from elementary particles up to condensed matter, the plasma state is an essential stage. In this state, matter consists of electrons and protons or ions. By the formation of bound states and by phase transitions, more complex states of matter such as liquids and solids evolve out of the plasma state. Consequently, plasmas are interesting and essential many-particle systems which are of importance for our fundamental understanding of condensed matter.

Plasmas play a fundamental role in nature. Probably more than 99 percent of visible matter in the universe exist in the plasma state. Plasmas exist, e.g., as interstellar gas, in stellar atmospheres, inside the sun, in giant planets, and in white dwarfs.

In the laboratories, plasmas were investigated first in connection with gas discharges. At the present time, plasmas are of interest in connection with magnetically confined fusion, and, at high densities, with the goal to achieve inertial fusion. Furthermore, laser produced plasmas, electron–hole plasmas in highly excited semiconductors, electrons in metals, ultracold plasmas and dusty plasmas are of importance.

Obviously, the development of a quantum statistical theory of charged many-particle systems is of great principal and practical importance. The theoretical investigation of charged many-particle systems is faced with a number of typical difficulties.

A plasma consists of freely moving charged particles, which produce charge and current densities and, therefore, an electromagnetic field; plasma particles interact with the electromagnetic field. In general, the dynamics of the plasma particles and that of the field have to be dealt with self-consistently. For many problems it is sufficient to account only for the coupling to the longitudinal field, i.e., to consider only the Coulomb interaction between the plasma particles.

The Coulomb interaction is characterized by its long range. This property of the Coulomb interaction leads to typical pecularities of charged many-particle systems, namely to the collective behavior of the plasma particles such as dynamical screening and plasma oscillations. In the theoretical description, the long range character leads to special difficulties, which turn out to be divergencies in the determination of thermodynamic or transport properties by means of cluster expansions. Binary or few-particle collision approximations are not appropriate to describe the collective interaction of plasma particles.

The collective behavior of a plasma has to be described in a self-consistent scheme of particles and fields. This was done for the first time by Debye. Debye determined the field produced by the charged system of particles in static approximation and invented the fundamental idea of a screened potential. Exploiting this idea, a number of problems of the theory of many-particle systems with Coulomb interaction were solved.

Later, in extension of the more elementary ideas of Debye, there was progress in carrying out ring summations in order to re-normalize cluster expansions as invented by Mayer for classical statistical mechanics and later by Macke in the field of quantum statistics. These techniques were further developed in the kinetic theory by Balescu, Lennard, Silin and Klimontovich where convergent collision integrals for plasmas were formulated.

Because of the complexity of plasma systems, for the complete theoretical description general methods of quantum statistics are necessary. Essential progress in the theory of nonideal plasmas was achieved by the introduction of quantum field-theoretical methods into statistical physics of equilibrium systems by Matsubara, Martin and Schwinger, and by Abrikosov, Gor'kov and Dzyaloshinski. On the basis of such techniques, the theory of the electron gas was formulated and further elaborated by Gell-Mann and Brueckner, by DuBois, Pines and Noziéres, and the equation of state for quantum plasmas was given by Montroll and Ward and by DeWitt.

Of special importance for the quantum statistics of plasmas is the generalization of the quantum field-theoretical methods to non-equilibrium systems which was achieved by Kadanoff and Baym and by Keldysh. In the papers of these authors, equations of motion for the real-time Green's functions, well known as Kadanoff–Baym equations, were derived. On the basis of the Kadanoff–Baym equations, essential progress was achieved in non-equilibrium statistical mechanics. Especially, one should remark that there now exists the possibility to deal with processes on very short time scales applying non-Markovian kinetic equations. In connection with the non-Markovian form of the collision integrals, the problem of conservation laws in nonideal plasmas was solved. On the basis of ideas of Keldysh and of Kadanoff and Baym, DuBois developed a quantum electrodynamics of plasmas and gave the foundation for a general theory of matter-radiation interaction.

As we want to stress the interrelation between theoretical methods and the physical topic, we will present the method of real-time Green's functions in statistical physics and its application to the complex problems of plasma physics.

To begin, we start with an introductory chapter on nonideal plasmas. On an elementary level, this chapter presents essential concepts of the physics of nonideal plasmas, such as static and dynamical screening and self-energy.