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FUDAN UNIVERSITY 1905-2005

Introduction to Soft Matter Physics

软物质物理导论

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献给复旦大学一百周年校庆

作者简介

周鲁卫，复旦大学物理系教授，祖籍安徽，1947年生于山东，中学毕业后去崇明农场5年，1979年复旦大学物理系物理专业及研究生理论物理专业毕业后，留校当理论物理助教。1986年获美国Temple大学物理学Ph.D.学位，后在美国洛杉矶加州大学固体科学中心、物理系做博士后，从事氧化物电磁学物性研究，1988年回国，任复旦大学物理系教师，曾任中国物理学会理事、上海市物理学会理事长。1993年起，从事软物质物理研究，在电、磁流变液的物性及其机理，以及生物医学物理方面探索，担任国际电、磁流变液会议国际顾问委员会成员。

通过面对研究生和本科生高年级的软物质物理课程教学，广泛了解软物质物理问题，编写教材《软物质物理导论》，尝试既从还原的角度理解软物质内部相互作用，又从整体及系统科学的角度，探讨软物质有别于硬物质极其丰富的复杂性。

Abstract

This textbook was developed over a period of 10 years for the author's lecture on soft matter physics for both graduate and undergraduate students in the Physics Department of Fudan University.

Soft matters are different from hard ones essentially due to former's relatively weak interaction which is comparable to $k_B T_{rm}$(T_{rm}=room temperature). It is this feature that results in the major characteristics of soft matters such as "strong reactions upon weak actions". This textbook not only concentrates on the basic interactions inside soft matters in a reductionist approach(Chap. 2, Chaps. 5 and 6), but also introduces the exploration works on the complexity of soft matters in methods of system science(Chap. 4). Soft matters is a bridge between hard matters and complex systems that show characteristics of deterministic chaos in nature.

As a "model animal"(a mouse, if you prefer) in soft matters, electrorheological(ER) fluids are introduced. While the properties and mechanisms of static ER effect are summerized(Chap. 5), this textbook puts its emphasis on the dynamic ER effects(Chap.6). The Onsager principle of least energy dissipation rate is adapted in the textbook to see how it governs the optimal paths of a system's deviation from and restoration to equilibrium. As another model animal, granular media is introduced(Chap. 7) to explain the thermodynamics of sands and its dynamics such as compartmentalization, pattern formation, and granular flow. Since many soft matters consist of light atoms, neutron scattering appears useful as a powerful tool and is worth mentioning(Chap.3), especially when a splashing neutron source is being erected in China.

Soft matter physics is full of unknowns(Chap. 1) as the subject is still at its infancy, making it highly attractive. If you like a challenging subject, you will most certainly fall in love with soft matter physics at first sight!

前　言

软物质，或者说复杂流体，是介乎硬物质和简单流体之间的凝聚态物质。近几十年来软物质物理这门学科发展迅速，不但在其每一个分支中新的研究成果层出不穷，而且其研究分支还不断涌现。本书在努力反映新研究成果的同时，尽力阐述本领域的基本知识和基本技能，介绍常用的研究方法和实验手段。希望本书能成为软物质物理的入门教材。

本书第一章介绍软物质物理的概貌。第二章探索组成软物质材料基本单元之间的相互作用。本书比较注意实验的叙述与实验思路发展和实验手段发展的叙述。软物质较多以轻元素组成，而像氢、碳、氧、氮等等轻元素的中子散射截面比 X 光散射截面大很多，而我国正在积极建设散裂中子源的大型科学项目，小角散射对软物质又是格外重要的一种手段。所以本教材在第三章中着重介绍怎样用中子散射，特别是小角中子散射获得软物质的结构。

由于软物质自组织的特点，一些复杂系统的特点比较容易体现在软物质中。而用复杂系统的观点来观察软物质能更深刻地理解软物质的物性。本书第四章专门讨论这部分内容。

作为软物质中物质和场相互作用的具体实例，也作为悬浮液和胶体的具体实例，本书的第五章着重叙述电流变液的相关内容。但这一章不仅叙述这一新材料的物性，也不仅叙述相关模型的发展，而是着重叙述解决这类胶体颗

粒在外场中相互作用问题的重要理论方法和实验手段。由于动态结构在外场中的变化是研究的难点和重点，本书也介绍了沈平课题组关于使用昂萨格原理解决相关问题的工作。掌握这些理论方法和实验手段对读者开展类似系统的动态研究非常重要。

颗粒系统是软物质物理中最为奇妙的一部分。第六章虽然以颗粒液态、颗粒固态和颗粒气态为线索介绍颗粒体系的性质，但其重点也是介绍相关的理论和实验研究办法，尽力让读者把注意力集中在颗粒体系的物理问题上。

软物质的发展路径能让每一位对软物质感兴趣的青年人看到一门交叉性很强的学科是怎样一步步艰难地发展起来的。本书希望着重叙述这一过程，使读者能了解软物质物理研究的基础内容和研究方法，并举一反三用于其他学科。

本人衷心感谢陶瑞宝、陶荣甲教授鼓励我进入软物质物理研究领域，感谢沈平、陆坤权、刘寄星、厚美瑛、童彭尔、温维佳、马红孺、马余强、黄吉平、陈唯、张建卫教授等许多同行的无数讨论，感谢王迅教授阅读部分书稿并提出修改建议。我还要感谢周高波对全书书稿做了仔细校勘；感谢往年软物质物理课程的助教：徐莉、鲍伟、伍秀峰、刘大康、张弛和李丛，他们协助丰富了本教材。

周鲁卫

2011 年 2 月于复旦大学

PREFACE

Soft matters, or complex fluids, are condensed matters between hard matters and simple fluids. Soft matter physics is rapidly developing in recent decades, not only because of its numerous research output in each branch of the subject, but also for its new branches that are emerging one after another. This textbook introduces the basic knowledge, some well-known research method and techniques, and it can be used as an introductory textbook for the undergraduate and graduate students.

In Chap. 1, the overview of the soft matter physics is introduced. The interactions between the fundamental units, such as colloidal particles, molecules or atoms, are described in Chap. 2. This textbook puts emphasis on the experimental process, as well as the development of experimental ideas and experimental techniques. Most of soft matters consist of light elements, such as hydrogen, carbon or oxygen, and their neutron scattering cross-sections are much larger than their X-ray ones. The small angle neutron scattering is especially useful for detecting the structures of soft matters, so Chap. 3 is devoted to the neutron scattering. We hope that students in soft matter area make a better use of the China Splashing Neutron Source some day.

Since the interaction of soft matters lies between that of hard matters and gases, the characteristics of complex systems, such as chaos and fractals, are usually easier to appear in soft matters. Viewing soft matters as complex systems would help better understand their behaviors. These are discussed in Chap. 4.

As an example of interactions of matters and fields in soft matters, also as an example of suspensions and colloids, Chapter 5 describes the knowledge of electrorheological fluids. Not only on the physical properties of the new materials, nor only on the development of the related models, this chapter emphasiges on the important theoretical and experimental methods of solving the interactions of the colloidal systems under external fields. The change of the dynamic structures of these systems under external fields is difficult point in the study, this chapter has introduced the work Ping Sheng's group on solving the problems using the Osager principle. Knowing the related theoretical ad experimental methods would help readers to deal the dynamic properties of the similar systems of soft matters.

The study of granular materials are most fascinating part in soft matter physics. Chapter 6 describes the properties of granular materials as granular liquid, solid and gas, however, readers should pay their attention to the theoretical and experimental methods, as well as related physical problems.

The path of the development of soft matter physics shows who are interested in it how a strongly interdisciplinary subject is growing with great difficult step by step. These contents draw special attention in this textbooks hoping readers to understand the basis contents and methods of soft matter physics and to use them in other subjects as well.

I would like to thank Profs. Ruibao Tao and Rongjia Tao for encouraging me to enter this research field, Profs. Ping Sheng, Kunquan Lu, Jixing Liu, Meiying Hou, Penger Tong, Weijia Wen, Hongru Ma, Yuqiang Yu, Jiping Huang, Wei Chen, Jianwei Zhang, and many others for numerous discussions, Prof. Xun Wang for reading a part of the manuscript and suggesting for modifications. I also want to thank Gaobo Zhou for his careful proofreading of entire text of the manuscript, and thank the teaching assistants of my lecture on soft matter physics, Li Xu, Wei Bao, Xiufeng Wu, Dakang Liu, Chi Zhang and Cong Li for helping enrich the textbook in past years.

Luwei Zhou
February, 2011
Fudan University

CONTENTS

Chapter 1

Major Characters of Soft Matters

1.1 Why Soft Matters

1.1.1 Why should study soft matter physics

French scientist Pierre-Gilles de Gennes won the Nobel Prize in Physics in 1991 "for discovering that methods developed for studying order phenomena in simple systems can be generalized to more complex forms of matter, in particular to liquid crystals and polymers" as described by the Nobel Prize committee. His Nobel Lecture was entiteed Soft Matter. [1.1] The French version of soft matter *matière molle* was invented as a joke by M. Veyssié in Orsay around 1970. [1.2] The term has a double meaning in French — both soft matter and useless or weak matter. It was introduced to describe something that goes plastic with bubbles of soap, from gels, elastomers, liquid crystals, cosmetic creams, mud, ceramic paste, etc. Soft matters are usually called complex fluids in the North America.

Soft matters refer to the soft condensed matters—the condensed matters that other than those in gas and solid states, but usually not including simple fluids. From the point of view of materials, soft matter physics is concerned with physical principles governing the behaviors of foams, liquid crystals, polymers, colloidal dispersions, micro emulsion, micelle, various types of biological liquids, suspensions, and even granular materials, because of their wide applications.

What are the major differences between the "soft" and "hard" matters?