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Advanced Condensed Matter Physics

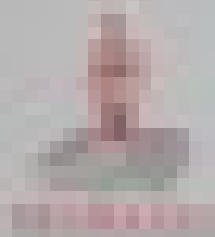
高等凝聚态物理

(影印版)

〔美〕桑德尔 (L. M. Sander) 著



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Advanced Condensed Matter Physics 凝聚态物理进阶

作者:

陈立群 陈立群 陈立群 陈立群

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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亲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

Advanced Condensed Matter Physics

Leonard M. Sander

Department of Physics, The University of Michigan



CAMBRIDGE
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To Mae & Evelyn

Preface

This book is intended as a textbook for a graduate course in condensed matter physics. It is based on many years' experience in teaching in the Physics department at The University of Michigan. The material here is more than enough for a one-semester course. Usually I teach two semesters, and in the second, I add material such as the renormalization group.

In this book advanced techniques such as Green's functions are not used. I have tried to introduce as many of the concepts of modern condensed matter physics as I could without them. As a result, some topics that are of central importance in modern research do not appear.

The problems are an integral part of the book. Some concepts that are used in later chapters are introduced as problems.

Students are expected to have a good background in statistical physics, non-relativistic quantum theory, and, ideally, know undergraduate Solid State physics at the level of Kittel (2005).

I decided to write this book as a result of coming back to teaching Condensed Matter after a number of years covering other subjects. I had hoped to find a substitute for the grand old standards like Ziman (1972) or Ashcroft & Mermin (1976) which I used at the beginning of my teaching career. Though there are newer texts that are interesting in many ways, I found that none of them quite fit my needs as an instructor. It is for the reader to decide how well I have succeeded in giving a modern alternative to the classics – they are very hard acts to follow.

Many people have helped me in writing this book. Craig Davis and Cagilyan Kurdak have been remarkably generous with their time, and found many errors. Jim Allen and Michal Zochowski have given valuable advice. I would like to particularly thank Brad Orr, Andy Dougherty, Dave Weitz, Jim Allen, Roy Clarke, and Meigan Aronson for figures. And, of course, my students have given invaluable feedback over more than three decades.

Contents

<i>Preface</i>	<i>page xi</i>
1 The nature of condensed matter	1
1.1 Some basic orders of magnitude	1
1.2 Quantum or classical	3
1.3 Chemical bonds	3
1.4 The exchange interaction	5
Suggested reading	6
Problems	6
2 Order and disorder	8
2.1 Ferromagnets	9
2.2 Crystals	16
2.3 Other ordered states	21
2.4 Order parameters	21
2.5 Disordered condensed matter	22
Suggested reading	23
Problems	23
3 Crystals, scattering, and correlations	25
3.1 Crystals	25
3.2 Fourier analysis and the reciprocal lattice	32
3.3 Scattering	37
3.4 Correlation functions	46
Suggested reading	50
Problems	51
4 Surfaces and crystal growth	53
4.1 Observing surfaces: scanning tunneling microscopy	53
4.2 Surfaces and surface tension	54
4.3 Roughening	60
4.4 Equilibrium crystal shapes	62
4.5 Crystal growth	64
Suggested reading	71
Problems	71

5	Classical and quantum waves	73
5.1	Lattice vibrations and phonons	73
5.2	Spin waves and magnons	102
5.3	Neutron scattering	107
5.4	Mössbauer effect	110
5.5	Two dimensions	111
	Suggested reading	112
	Problems	112
6	The non-interacting electron model	114
6.1	Sommerfeld model	114
6.2	Thermally excited states and heat capacity	120
6.3	Band theory	122
	Suggested reading	135
	Problems	135
7	Dynamics of non-interacting electrons	139
7.1	Drude model	139
7.2	Transport in Sommerfeld theory	141
7.3	Semiclassical theory of transport	143
7.4	Scattering and the Boltzmann equation	146
7.5	Donors and acceptors in semiconductors	151
7.6	Excitons	152
7.7	Semiconductor devices	153
7.8	Large magnetic fields	156
	Suggested reading	168
	Problems	169
8	Dielectric and optical properties	172
8.1	Dielectric functions	172
8.2	The fluctuation-dissipation theorem	174
8.3	Self-consistent response	177
8.4	The RPA dielectric function	181
8.5	Optical properties of crystals	187
	Suggested reading	189
	Problems	189
9	Electron interactions	193
9.1	Fermi liquid theory	193
9.2	Many-electron atoms	198
9.3	Metals in the Hartree–Fock approximation	202
9.4	Correlation energy of jellium	205
9.5	Inhomogeneous electron systems	210
9.6	Electrons and phonons	216

9.7	Strong interactions and magnetism in metals	220
	Suggested reading	224
	Problems	224
10	Superfluidity and superconductivity	226
10.1	Bose–Einstein condensation and superfluidity	227
10.2	Helium-3	235
10.3	Superconductivity	236
10.4	Microscopic theory	241
10.5	Ginsburg–Landau theory	253
10.6	Josephson effect	259
	Suggested reading	261
	Problems	261
	<i>References</i>	263
	<i>Index</i>	269

Condensed matter physics is the study of large numbers of atoms and molecules that are “stuck together.” Solids and liquids are examples. In the condensed state many molecules interact with each other. The physics of such a system is quite different from that of the individual molecules because of *collective effects*: qualitatively new things happen because there are many interacting particles. The behavior of most of the objects in our everyday experience is dominated by collective effects. Examples of materials where such effects are important are crystals and magnets.

This is a vast field: the subject matter could be taken to include traditional solid state physics (basically the study of the quantum mechanics of crystalline matter), magnetism, fluid dynamics, elasticity theory, the physics of materials, aspects of polymer science, and some biophysics. In fact, condensed matter is less a field than a collection of fields with some overlapping tools and techniques. Any course in this area must make choices. This is my personal choice.

In this chapter I will discuss orders of magnitude that are important, review ideas from quantum mechanics and chemistry that we will need, outline what holds condensed matter together, and discuss how order arises in condensed systems. The discussion here will be qualitative. Later chapters will fill in the details.

1.1 Some basic orders of magnitude

To fix our ideas, consider a typical bit of condensed matter, a macroscopic piece of solid copper metal. As we will see later it is best to view the system as a collection of cuprous (Cu^+) ions and conduction electrons, one per atom, that are free to move within the metal. We discuss some basic scales that will be important for understanding the physics of this piece of matter.

Lengths A characteristic length that will be important is the distance between the Cu atoms. In a solid this distance will be of order of a chemical bond length:

$$L \approx 3 \text{ \AA} \approx 3 \times 10^{-8} \text{ cm.} \quad (1.1)$$

Note that this is very tiny on the macroscopic scale. The whole art of condensed matter physics consists in bridging the gap between the atomic scale and the macroscopic properties of condensed matter.

Energies We can ask about the characteristic energy scales for the sample. One important energy scale is the binding energy of the material per atom. A closely related quantity is the melting temperature in energy units:

$$1357 \text{ K} = 0.11 \text{ eV.} \quad (1.2)$$

This is a typical scale to break up the material. If we probe at much larger energies (KeV, for example) we will be probing the inner shells of Cu, namely the domain of atomic physics, or at MeV, the Cu nucleus, i.e. nuclear physics.

Cu has an interesting color (it is copper colored, in fact), so we might expect something interesting at the scale of the energy of ordinary light, namely,

$$E \approx \hbar\omega_{\text{opt}} \sim 3 \text{ eV} \quad (1.3)$$

which is also the strength of a typical chemical bond. A somewhat larger, but comparable scale is that of the Coulomb interaction of two electrons a distance L apart:

$$E \approx e^2/L \approx 5 \text{ eV.} \quad (1.4)$$

These energies are low even for atomic physics. This means that in our study of condensed matter we will always be interested only in the outer (valence electrons) which are least bound.

Speeds When a piece of Cu carries an electrical current of density, \mathbf{j} , the conduction electrons move at a drift velocity \mathbf{v}_d :

$$\mathbf{j} = ne \mathbf{v}_d \quad (1.5)$$

where n is the number density of conduction electrons and e is the charge on the electron. For ordinary sized currents we find a very small speed, $v_d \approx 0.01 \text{ cm/sec}$.

There is another characteristic speed, the mean thermal speed, v_T of the Cu ions when they vibrate at finite temperature. We estimate v_T as follows. From the Boltzmann equipartition theorem the mean kinetic energy of an ion is:

$$Mv_T^2/2 \sim k_B T. \quad (1.6)$$

Here T is the absolute temperature, k_B is Boltzmann's constant, M is the mass of a Cu ion, and v_T is the mean thermal velocity. At room temperature we get $v_T \sim 3 \times 10^4 \text{ cm/sec}$.

There is a larger speed associated with the electrons, namely the quantum mechanical speed of the valence electrons. We estimate this speed as [frequency of an optical transition] \times length:

$$v \sim (E/\hbar)(L) \approx 10^7 \text{ cm/sec.} \quad (1.7)$$

As we will see below, there is another relevant speed, the magnitude of the Fermi velocity, which is of the same order.

In any case, all of these speeds are small compared to the speed of light. Thus, we seldom need the theory of relativity in condensed matter physics. (An exception is the spin-orbit interaction of heavy elements.)

Large numbers and collective effects The essential point of the subject is that we deal with very large *numbers* of ions and electrons, $\approx 10^{27}$ in a macroscopic sample. In a famous essay P. W. Anderson (1972) pointed out the significance of this fact. When many things interact we often generate new phenomena, sometimes called emergent phenomena. Or, as Anderson put it, “more is different.” Some examples of collective effects that we will emphasize in this book are the existence of *order* of various types, e.g. crystalline order, magnetic order, and superconducting order.

1.2 Quantum or classical

We have seen that we are interested in non-relativistic physics. We can go further: for the case of Cu there are conduction electrons and Cu^+ ions. What type of physics is applicable to each? In particular, do we need quantum mechanics? A useful criterion is to compare the de Broglie wavelength of the relevant particle, $\lambda = h/mv$, to the interparticle spacing.

For the ions, the relevant speed is v_T which we estimated above. Thus:

$$\lambda = h/(2Mk_B T)^{1/2} \approx 10^{-9} \text{ cm} \ll L. \quad (1.8)$$

This is smaller than the spacing by an order of magnitude. For all ions in solids (except for He and H at very low temperatures) we can use classical mechanics. (As we will see, for vibrations of ions at low T , we need quantum mechanics too.)

For the electrons the situation is different because the electron mass, m , is 63×1800 times smaller than the mass of a Cu ion, so we get

$$\lambda = h/(2mk_B T)^{1/2} \approx 3 \times 10^{-7} \text{ cm} \gg L. \quad (1.9)$$

Electrons are quantum mechanical for all temperatures.

1.3 Chemical bonds

Matter condenses because atoms and molecules attract one another. In the condensed state they are connected by chemical bonds. This is the “glue” that holds condensed matter together. We will summarize here some notions from chemistry which we will need in the sequel.

van der Waals’ bonds At long ranges the dominant interaction between neutral atoms or molecules is the van der Waals interaction which arises from the interaction of fluctuating induced dipoles. For two neutral molecules (or atoms) a distance d apart this effect gives

rise to a potential energy of interaction given by:

$$V(r) \sim -1/r^6. \quad (1.10)$$

This equation is universally true if the molecules are far apart compared to the size of their electronic clouds. For closed shell atoms and molecules such as Ar and H₂ that do not chemically react, the van der Waals' interaction is the attractive force that causes condensation. Since this is a weak, short-range force, materials bound this way usually have low melting points.

A rough argument for the r^{-6} dependence is as follows: suppose there is a fluctuation (a quantum fluctuation, in fact) on one of two molecules so that an instantaneous dipole moment, p_1 , arises. This gives rise to an electric field of order $E \sim p_1/d^3$ at the other molecule. This electric field polarizes the other atom. To understand this, we introduce a concept that we will use later, the *polarizability*, α , of the molecule. It is defined by:

$$\mathbf{p}_{\text{ind}} = \alpha \mathbf{E}, \quad (1.11)$$

where \mathbf{p}_{ind} is the induced dipole moment. Note that in our system of units the polarizability, α , has units of volume. It is roughly the molecular volume. Thus $p_2 \sim \alpha p_1/d^3$. This finally gives for identical molecules the fluctuating dipole-dipole interaction:

$$V \sim p_1 p_2 / d^3 \sim \alpha p_1^2 / d^6. \quad (1.12)$$

Since this expression depends on p_1^2 there is a time-averaged value for the potential. It is easy to show that the dipoles will be antiparallel so that the interaction is attractive. An actual calculation of the coefficient of r^{-6} , that is, of the average of p_1^2 , can be done (in simple cases) using quantum mechanical perturbation theory.

Ionic bonds The chemistry of the valence electrons in a compound can lead to charge transfer, e.g.:



In this case there will be strong forces due to the charges, and the ions will be bound by the Coulomb interaction:

$$V(r) = Zq_1 q_2 / r.$$

This is called ionic binding. Solid NaCl, table salt, is bound in this way. Ionic solids often have very large binding, and very large melting points.

Covalent bonds In elements with s and p electrons in the outer shell, covalent sp^3 orbitals give rise to directed bonds where electrons between ions glue together the material. Semiconductors such as Si, Ge, are bonded this way, as well as polymers and many biological materials. There are intermediate cases between the covalent and ionic materials, such as III-V semiconductors like GaAs.

Hydrogen bonds These arise in materials that contain H such as ice. The proton participates in the bonding. This is very important in biological materials.