Modern Condensed Matter Physics

Modern Condensed Matter Physics brings together the most important advances in the field from recent decades. It provides instructors teaching graduate-level condensed matter courses with a comprehensive and in-depth textbook that will prepare graduate students for research or further study alongside reading more advanced and specialized books and research literature in the field.

This textbook covers the basics of crystalline solids as well as analogous optical lattices and photonic crystals, while discussing cutting-edge topics such as disordered systems, mesoscopic systems, many-body systems, quantum magnetism, Bose–Einstein condensates, quantum entanglement, and superconducting quantum bits.

Students are provided with the appropriate mathematical background to understand the topological concepts that have been permeating the field, together with numerous physical examples ranging from the fractional quantum Hall effect to topological insulators, the toric code, and Majorana fermions. Exercises, commentary boxes, and appendices afford guidance and feedback for beginners and experts alike.

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Preface

This textbook is intended for both introductory and more advanced graduate-level courses in condensed matter physics and as a pedagogical reference for researchers in the field. This modern textbook provides graduate students with a comprehensive and accessible route from fundamental concepts to modern topics, language, and methods in the rapidly advancing field of quantum condensed matter physics.

The field has progressed and expanded dramatically since the publication four decades ago of the classic text by Ashcroft and Mermin [1], and its name has changed from Solid State Physics to Condensed Matter Physics, reflecting this expansion. The field of inquiry is vast and is typically divided into two halves. The first, often called "soft matter," covers the classical statistical physics of liquid crystals, glassy materials, polymers, and certain biological systems and materials. This area is nicely addressed in the textbook of Chaikin and Lubensky [2]. The second area, often called "hard matter" or "quantum matter," primarily covers the quantum physics of electrons in solids but these days also includes correlated quantum states of ultra-cold atomic gases and even photons. While a number of good textbooks [3–5] address various aspects of hard matter, the present text offers broader and more in-depth coverage of the field and provides physical intuition through many deep phenomenological descriptions, in addition to introducing the required mathematical background.

The present text is aimed primarily at graduate students and researchers in quantum condensed matter physics and provides encyclopedic coverage of this very dynamic field. While sharing a similar starting point with Ashcroft and Mermin, we have attempted to cover the aforementioned new developments in considerably greater depth and detail, while providing an overarching perspective on unifying concepts and methodologies. Chapters 1–9 cover traditional introductory concepts, but we have made considerable effort to provide a modern perspective on them. The later chapters introduce modern developments both in theory and in experiment. Among the new topics are coherent transport in mesoscopic systems, Anderson and many-body localization in disordered systems, the integer and fractional quantum Hall effects, Berry phases and the topology of Bloch bands, topological insulators and semimetals, instabilities of Fermi liquids, modern aspects of quantum magnetism (e.g. spinons, the Haldane gap, spin liquids, and the toric code), quantum entanglement, Bose–Einstein condensation, a pedagogical introduction to the phenomenology of superfluidity and superconductivity, superconducting quantum bits (qubits), and finally a modern review of BCS theory that includes unconventional pairing, high-temperature superconductivity, topological superconductors, and majorana fermions. We have also attempted to make contact with other fields, in particular ultra-cold atomic gases, photonic crystals, and quantum information science, emphasizing the unifying principles among different branches of physics. For this reason the text should also be of interest to students and practitioners outside condensed matter physics.

The text is intended to be accessible and useful to experimentalists and theorists alike, providing an introduction both to the phenomenology and to the underlying theoretical description. In particular, we provide the mathematical background needed to understand the topological aspects of condensed matter systems. We also provide a gentle and accessible introduction to scaling and renormalization group methods with applications to Anderson localization, the Kondo problem, and the modern approach to the BCS problem. The text assumes prior knowledge of quantum mechanics and statistical physics at the level of typical first-year graduate courses. Undergraduate preparation in condensed matter physics at the level of Kittel [6] would be useful but is not essential. We make extensive use of harmonic oscillator ladder operators but almost completely avoid second quantization for fermions until Chapter 17. In addition, we provide a pedagogical appendix for the reader to review second quantization.

Recent decades have seen the application of advanced methods from quantum field theory which provide effective descriptions of "universal" features of strongly correlated many-body quantum systems, usually in the long-wavelength and low-energy limit [7–15]. The present text provides a pedagogical gateway to courses on these advanced methods by introducing and using the language of many-body theory and quantum field theory where appropriate.

This book has evolved over several decades from course notes for graduate condensed matter physics taught by the authors at Indiana University and Florida State University, respectively. The content exceeds the amount of material which can be covered in a one-year course but naturally divides into an introductory portion (Chapters 1–10) which can be covered in the first semester. For the second semester, the instructor can cover Chapters 11–15 and then select from the remaining chapters which cover the fractional quantum Hall effect, magnetism, superfluidity, and superconductivity.

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