Fundamentals of Condensed Matter and Crystalline Physics
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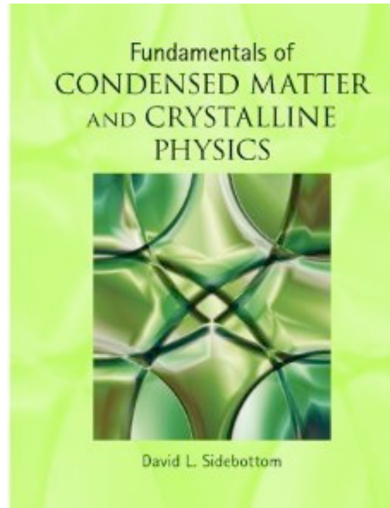

Synopsis: An undergraduate level introduction to key themes in condensed matter physics intended to compliment a one-semester introduction to condensed matter physics or enhance a one-semester course course on traditional solid state physics. Emphasis is placed on linking condensed matter themes (amorphous and self-similar structures, bulk and microscopic dynamics, scaling laws) with more traditional solid state physics themes (crystal structure, phonons and band theory) in a reasonably seamless fashion. Key themes include the description of particle structures (both crystalline and amorphous) with a development of scattering theory connected with these structures; description of particle dynamics including both lattice vibrations, conduction electrons, response functions and random processes in liquids (e.g. hydrodynamic modes, Brownian motion and polymer dynamics); development of the role of scaling laws, criticality, and universality that emerge most prominently in phase transitions near a critical point. This textbook was specifically written as a hybridization of Kittel's popular solid state physics text and designed to expand upon traditional crystal physics (contained in the first 7 chapters of Kittel) with standard (often noncrystalline) condensed matter themes in a seamless, continuous manner. It is unique in its balanced approach to condensed matter physics that is delivered in the style of an undergraduate textbook like Kittel's.

Outline: The textbook contains 18 chapters that are divided into four main categories: Structure, Scattering, Dynamics, and Transitions. A brief summary of each chapter is as follows.

I. Structure

1. Crystal Structure: Students are introduced to the structure of crystals defined by combination of a space lattice and basis set. Symmetry is highlighted as an important characteristic that limits unique lattices to a discrete Bravais set. The cubic and hexagonal lattices are examined in further detail to introduce concepts of coordination and packing efficiency. (This chapter is similar to Kittel's Ch. 1)

2. Amorphous Structure: The crystal structures of the previous chapter are contrasted by those of amorphous solids. Students are introduced to the notion of an ensemble-averaged pattern of particle correlations as defined by the pair distribution function. The random close pack and continuous random network structures are examined in further detail to emphasize the distribution of coordination and bond angles found in amorphous matter.

3. Bonds and Cohesion: The five major bonding types are reviewed together with a development of the cohesion energy of both van der Waal and ionic crystals. The cohesion of a van der Waals liquid or glass is also introduced as an application of the pair distribution function. (This chapter is similar to Kittel's Ch. 3)

4. Magnetic Structure: Concepts of order and disorder developed in Chapters 1 and 2 are augmented by the notion of systems with orientational order. Students are introduced to magnetic materials (diamagnetic, paramagnetic and ferromagnetic) and the role of the exchange interaction in promoting correlated regions of orientational order. (This chapter is a condensed version of Kittel's Ch. 11, 12)

II. Scattering

5. Scattering Theory: The scattering of EM waves from electrons of matter is developed from the ground up beginning with dipole scattering from a single electron, the consequences of interference of scattering by two electrons, and the atomic form factor as a generalization of scattering from the electron cloud of an atom for a given scattering wave vector. Students are then introduced to the static structure factor as a measure of the overall interference caused by particle positions in a solid and its Fourier relationship to the density-density correlation function. Along the way, students are reminded that the structure factor is invariant with respect to the source of waves (e.g., light or neutrons).

6. Scattering by Crystals: The scattering from crystals is considered. The orderly pattern of particle positions is shown to cause scattering only at a discrete set of scattering wavevectors which then define a reciprocal lattice. The traditional Bragg scattering law is derived as a consequence and the role of lattice planes (Miller indices) in X-ray diffraction is presented. (This chapter is comparable to Kittel's Ch. 2, although developed from the standpoint of the structure factor first and Bragg's law afterwards)

7. Scattering by Amorphous Matter: The static structure factor is shown to reduce to a Fourier transform of the pair distribution function for amorphous materials. The Fourier relationship is illustrated by amorphous germanium where the structure factor is Fourier inverted to produce the radial distribution function and demonstrate features of short range order. Short range order is contrasted by long range density fluctuations that scatter visible light and the static structure factor is shown also to be a Fourier transform of the van Hove correlation function describing these density fluctuations. A brief introduction to SAXS and SANS is provided to emphasize the significance of the scattering wavevector as a variable lengthscale for probing intermediate range order.

8. Self-similar Structures and Liquid Crystals: The scattering and structure of self-similar objects (polymers and aggregates) are introduced and shown to produce power law properties in the static structure factor. Students are introduced to both the random walk problem and the self-similarity of fractals in nature. Soot aggregates are used as an example of the multiple levels of structure contained in the static structure factor over a wide range of scattering wavevectors. Also introduced in this chapter is the structure of liquid crystals and microemulsions emphasizing their intermediate symmetry and properties of self-assembly.

III. Dynamics

9. Liquid Dynamics: The static structure factor is generalized to a time-dependent dynamic structure factor and shown to be related (by Fourier transform) to a time-dependent version of the van Hove correlation function. The random walk process is revisited and Brownian motion presented. The Rayleigh-Brillouin spectrum of a liquid is derived and shown to be the result of both diffusive and propagating density fluctuations. Students are introduced to the novelty of the glass transition emphasizing the ambiguity between liquid and solid states and its thermodynamic consequences. The random walk is revisted yet again to discuss both the Rouse and reptation dynamics of polymer liquids.

10. Crystal Vibrations: Students are introduced to the vibrational properties of a crystal lattice. The dispersion relations for both the monatomic and diatomic lattice are developed with an emphasis on the significance of the Brillouin zone as a resonant point for Bragg scattering. Phonons are introduced as the quantum of vibrational energy resulting from constraints on the allowed vibrational wavelengths and inelastic scattering from phonons is derived as a straightforward extension of the dynamic structure factor. (This chapter is similar to Kittel's Ch. 4, although the development of inelastic scattering is more obvious to the reader)

11. Thermal Properties: Thermal properties of the crystal lattice are considered in terms of the statistics of phonons. The specific heat is derived for both the Einstein and Debye models and the thermal conductivity is shown to result from phonon-phonon scattering. A comparison is made with amorphous materials where significant departures are seen at low temperatures. Two level systems and phonon localization are introduced and shown to account for the low temperature anomalies. (This chapter is similar to Kittel's Ch. 5, except for the additional development of amorphous topics: two level systems and phonon localization)

12. Electrons: The Free Electron Model: The electronic band structure of crystals is presented in two chapters. In the first chapter, students are introduced to the dilemma of classical models (Drude) for electronic motion and its contribution to the heat capacity and are shown how a simple "square well" approach (free electron model) provides ready explanations. (This chapter is similar to Kittel's Ch. 6)

13. Electrons: Band Theory: In this continuation of electronic properties, the nearly free electron (Kronig-Penney) model, emphasizing the role of a periodic potential and it consequences in the production of energy bands and energy gaps, is introduced. This is followed with an introduction to intrinsic and extrinsic (doped) semiconductors and the pn-junction as an important device. A brief discussion of electron localization (Anderson transition) in amorphous materials is also included. (Aside from the inclusion of electron localization, this chapter is a condensed version of Kittel's Chs. 7 and 8)

14. Bulk Dynamics and Response: Bulk dynamics are developed with an emphasis on the role of frequency-dependent response functions as a measure of microscopic dynamics. Response functions are shown to be Fourier transforms of corresponding time-dependent relaxations and provide a direct measure of energy storage and loss. Students are introduced to the fluctuation-dissipation theorem as an inherent link between bulk energy dissipation and intrinsic thermodynamic fluctuations.

IV. Transitions

15. Introduction to Phase Transitions: Students are familiarized with the phase diagrams that describe both fluids and magnetic phase transitions. First and second order transitions are introduced with special emphasis on critical phenomena including critical opalescence and the role of large-scale fluctuations in the order parameter. Universality and laws of corresponding states are discussed and the significance of a diverging correlation length is emphasized.

16. Percolation Theory: A comprehensive theory of percolation is presented emphasizing its random nature and similarity to second order phase transitions where, now, critcal divergences are associated with growing clusters of a self-similar morphology. Scaling concepts such as finite-sized scaling and renormalization are introduced as an extension of the self-similarity. Several examples of the application of percolation theory are provided including a development of anomalous diffusion.

17. Mean Field Theory and Renormalization: The mean field theories for the van der Waals model and Ising spin model are introduced to demonstrate laws of corresponding states and universality in critical exponents. The Landau theory of phase transitions is introduced as a generic template for second order transitions described by an arbitrary order parameter. Renormalization is revisited for the Ising model to show how important scaling relations can be determined.

18. Superconductivity: Superconductivity phenomena (including the London equation/Meissner effect and penetration length) are reviewed within the context of a second order phase transition. The BCS theory is introduced in a conceptual manner emphasizing the electron-phonon coupling needed for attractive interactions and the boson-like nature of Cooper pairs. Ginzburg-Landau theory is applied to illustrate the second-order nature of the transition and to understand the origins of the Type II, vortex, phase. (This chapter is similar to Kittel's Ch. 10)

Appendix: An appendix titled "Toolbox" is included that reviews some of the prerequisite knowledge concerning Fourier transforms and statistical mechanics that undergraduate students may not have had significant exposure to at this point in their training.