INTRODUCTION TO CONDENSED MATTER PHYSICS

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Abstract:

Condensed matter physics is the field of physics that deals with the macroscopic and microscopic physical properties of matter. In particular it is concerned with the "condensed" phases that appear whenever the number of constituents in a system is extremely large and the interactions between the constituents are strong. The most familiar examples of condensed phases are solids and liquids, which arise from the electromagnetic forces between atoms. Condensed matter physicists seek to understand the behavior of these phases by using physical laws. In particular, they include the laws of quantum mechanics, electromagnetism and statistical mechanics.

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Introduction:

Condensed matter physics is concerned with the behavior of large aggregates of atoms or molecules in liquid or solid form. It is one of the largest branches of physics, with a wide variety of different systems, approaches, challenges and concepts. Often, it is subdivided in soft condensed matter physics and hard condensed matter physics. While the transition between the two branches is gradual, one way to distinguish them is by the role of quantum mechanics for the elementary excitations of the systems [1].

Soft condensed matter physics (the physics of polymers, liquid crystals, the statistical mechanics of bio-molecules etc.) is frequently termed "$\hbar = 0$"-physics, stressing that classical dynamics suffices for an understanding of the motion and aggregation of these systems. In distinction, for hard condensed matter physics, i.e. " $\hbar = 1$"-physics, the motion of electrons, lattice vibrations etc. is determined by Schrödinger’s equation [2].

Physics is a basic science and its ultimate purpose is the accumulation of new knowledge. In addition, condensed matter physics is closely connected to materials science as well as mechanical, chemical, and electric engineering that focus on the design of novel materials and devices, ranging from better batteries, thermoelectric devices for waste heat conversion to superconductors, magnets, all the way to better agents in drug delivery [3]. This applied aspect of condensed matter physics is exciting and important. Still, we should not forget that the field also contributes to the accumulation of fundamental knowledge and to major philosophical issues of our times. The value of Planck.s quantum, ħ, or of the electron charge, e, are defined via solid state effects in semiconductors and metals (the quantum Hall effect and the Josephson effect). It is quite amazing that these fundamental constants of nature are not determined in an experiment at a particle accelerator, but rather in a solid state laboratory [4]. Other frequently cited examples about the fundamental importance of condensed matter physics are that the famous Higgs particle was first proposed in the context of superconducting phase transitions, that asymptotic freedom (important for our current understanding of hadronization of quarks) occurs in case of the Kondo effect of a magnetic impurity in a metal, that fractional charges emerge naturally in the context of the fractional Quantum Hall effect etc. etc. The beauty of condensed matter physics is that it combines hands-on applications with the development of fundamentally new concepts, often even in the same material!. Let’s discuss one epistemological issue that is heavily debated these days: Particle and string theorists search to find a better way to formulate the fundamental laws of physics [5].

This is very exciting research. But suppose for a moment, we knew the fundamental "theory of everything" (TOE). Does this mean that the physics would stop existing as a basic science? Well, in condensed matter physics we have a TOE since 1927, yet major discoveries continue to take place.

Thus, the "theory of everything" of condensed matter physics is well known and established [6]. It would however be foolish to believe that phenomena like superconductivity, the fractional quantum Hall effect, electron localization etc. could be derived. Instead, a combination of experimental ingenuity, symmetry based reasoning, and a clever analysis of the relevant time and length scales of a given problem (formalized in terms of the renormalization group theory) ultimately allows for such conclusions and lead to conceptually new insights [7]. The message is that the knowledge of a fundamental "theory of everything" has very little bearing on the fascinating possibilities that emerge when many particles interact with each other and organize into new states of matter. There is no reason, other than habit and accepted custom, to believe that the situation is much different in other areas of physics, such as particle physics or quantum gravity.

The study of quantum condensed matter is a very hard problem. We consider in general interacting many-body systems of 1024 degrees of freedom, typically represented by the electrons in a solid. Since the Hilbert space is exponentially large in the number of degrees of freedom, any 'brute force' theoretical approach using the resources of classical computers to this problem must fail. A quantum computer might help, but is not (yet) available. Nevertheless, impressive progress has been made in the theoretical study of solid state systems, thanks to two bold simplifications:

Separation of energy scales: In contrast to high-energy physics, where new physics appears at ever higher energies, in condensed matter physics the phenomena of interest typically appear at very low energies. To put it boldly, these two energy frontiers are where we can expect new physics to appear. Everything in between is, at least on a fundamental level, understood. Different physical phenomena can be separated by the energy scale at which they appear, and their impact on the phenomena at smaller energy scales can often be incorporated in some effective form [8]. For example, it is in many cases sufficient to consider the crystal as a rigid lattice of ions in which the electrons move or to only consider the coupling between the electrons and the low-energy vibration (phonon) modes of the crystal. As another example, the Coulomb interaction between electrons can in some cases be neglected so that one solves only the problem of free electrons moving in the background potential of the ions. A plethora of more sophisticated approximations has been developed, some of which we will encounter in this course.

Use of symmetries: The formation of a crystal breaks (spontaneously) the Lorentz symmetry of open space. At first sight, this appears to be problematic, as one cannot take advantage of this symmetry group to describe the low-energy properties of electrons, in the same way as one can identify allowed terms in a Lagrangian in high-energy physics, say. However, the crystal breaks the symmetry not completely, but retains a discrete translation symmetry and potentially other symmetries such as rotations, mirror reections, inversion, time-reversal symmetry and so on. In addition, at low energies effective symmetries can emerge that are not shared by the whole crystal. For example, while a cubic crystal has only four-fold rotational symmetry, the dispersion of electrons at low electron-density might still be well described as parabolic, with an effective continuous rotation symmetry. This renders the situation much better than, say, in bio-chemistry, where one cannot take much advantage of constraining the problems by symmetries.

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