

Quantum Mechanics_Condensed matter physics

Condensed matter physics is a branch of physics that deals with the physical properties of condensed Phases of matter.^[1] Condensed matter physicists seek to understand the behavior of these phases by using physical laws. In particular, these include the laws of quantum mechanics, electromagnetism and statistical mechanics.

The most familiar condensed phases are solids and liquids, while more exotic condensed phases include the superconducting phase exhibited by certain materials at low temperature, the ferromagnetic and antiferromagnetic phases of spins on atomic lattices, and the Bose-Einstein condensate found in cold atomic systems. The study of condensed matter physics involves measuring various material properties via experimental probes along with using techniques of theoretical physics to develop mathematical models that help in understanding physical behavior.

The diversity of systems and phenomena available for study makes condensed matter physics the most active field of contemporary physics: one third of all American physicists identify themselves as condensed matter physicists,^[2] and The Division of Condensed Matter Physics (DCMP) is the largest division of the American Physical Society.^[3] The field overlaps with chemistry, materials science, and nanotechnology, and relates closely to atomic physics and biophysics. Theoretical condensed matter physics shares important concepts and techniques with theoretical particle and nuclear physics.^[4]

A variety of topics in physics such as crystallography, metallurgy, elasticity, magnetism, etc., were treated as distinct areas, until the 1940s when they were grouped together as Solid state physics. Around the 1960s, the study of physical properties of liquids was added to this list, and it came to be known as condensed matter physics.^[5] According to physicist Phil Anderson, the term was coined by him and Volker Heine when they changed the name of their group at the Cavendish Laboratories, Cambridge from "Solid state theory" to "Theory of Condensed Matter",^[6] as they felt it did not exclude their interests in the study of liquids, nuclear

matter and so on.[7] The Bell Labs (then known as the *Bell Telephone Laboratories*) was one of the first institutes to conduct a research program in condensed matter physics.[5]

References to "condensed" state can be traced to earlier sources. For example, in the introduction to his 1947 "Kinetic theory of liquids" book,[8] Yakov Frenkel proposed that "The kinetic theory of liquids must accordingly be developed as a generalization and extension of the kinetic theory of solid bodies. As a matter of fact, it would be more correct to unify them under the title of "condensed bodies".

History

Classical physics



Heike Kamerlingh Onnes and Johannes van der Waals with the helium "liquefactor" in Leiden(1908)

One of the first studies of condensed states of matter was by English chemist Humphry Davy, in the first decades of the 19th century. Davy observed that of the 40 chemical elements known at the time, 26 had metallic properties such as lustre, ductility and high electrical and thermal conductivity.[9] This indicated that the atoms in Dalton's atomic theory were not indivisible as Dalton claimed, but had inner structure. Davy further claimed that elements that were then believed to be gases, such

as nitrogen and hydrogen could be liquefied under the right conditions and would then behave as metals.[10][notes 1]

In 1823, Michael Faraday, then an assistant in Davy's lab, successfully liquefied chlorine and went on to liquefy all known gaseous elements, with the exception of nitrogen, hydrogen and oxygen. [9] Shortly after, in 1869, Irish chemist Thomas Andrews studied the Phase transition from a liquid to a gas and coined the term critical point to describe the condition where a gas and a liquid were indistinguishable as phases, [12] and Dutch physicist Johannes van der Waals supplied the theoretical framework which allowed the prediction of critical behavior based on measurements at much higher temperatures. [13] By 1908, James Dewar and H. Kamerlingh Onnes were successfully able to liquefy hydrogen and then newly discovered helium, respectively. [9]

Paul Drude proposed the first theoretical model for a classical electron moving through a metallic solid. [4] Drude's model described properties of metals in terms of a gas of free electrons, and was the first microscopic model to explain empirical observations such as the Wiedemann–Franz law. [14][15] However, despite the success of Drude's free electron model, it had one notable problem, in that it was unable to correctly explain the electronic contribution to the specific heat of metals, as well as the temperature dependence of resistivity at low temperatures. [16]

In 1911, three years after helium was first liquefied, Onnes working at University of Leiden discovered superconductivity in mercury, when he observed the electrical resistivity of mercury to vanish at temperatures below a certain value. [17] The phenomenon completely surprised the best theoretical physicists of the time, and it remained unexplained for several decades. [18] Albert Einstein, in 1922, said regarding contemporary theories of superconductivity that “with our far-reaching ignorance of the quantum mechanics of composite systems we are very far from being able to compose a theory out of these vague ideas”. [19]

Advent of quantum mechanics

Drude's classical model was augmented by Felix Bloch, Arnold Sommerfeld, and independently by Wolfgang Pauli, who used quantum mechanics to describe the motion of a quantum electron in a periodic lattice. In particular, Sommerfeld's theory accounted for the Fermi–Dirac statistics satisfied by electrons and was better able to

explain the heat capacity and resistivity.[16] The structure of crystalline solids was studied by Max von Laue and Paul Knipping, when they observed the X-ray diffraction pattern of crystals, and concluded that crystals get their structure from periodic lattices of atoms.[20] The mathematics of crystal structures developed by Auguste Bravais, Yevgraf Fyodorov and others was used to classify crystals by their symmetry group, and tables of crystal structures were the basis for the series *International Tables of Crystallography*, first published in 1935.[21] Band structure calculations was first used in 1930 to predict the properties of new materials, and in 1947 John Bardeen, Walter Brattain and William Shockley developed the first Semiconductor-based transistor, heralding a revolution in electronics.[4]



A replica of the first point-contact transistor in Bell labs

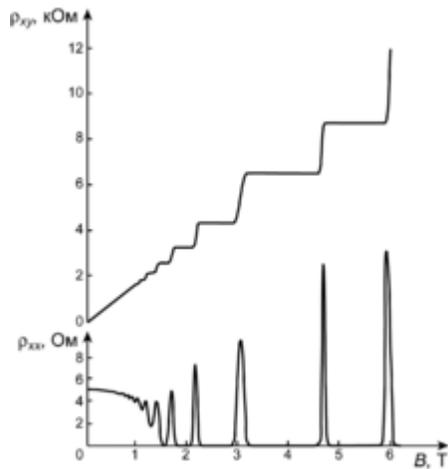
In 1879, Edwin Herbert Hall working at the Johns Hopkins University discovered the development of a voltage across conductors transverse to an electric current in the conductor and magnetic field perpendicular to the current.[22] This phenomenon arising due to the nature of charge carriers in the conductor came to be known as the Hall effect, but it was not properly explained at the time, since the electron was experimentally discovered 18 years later. After the advent of quantum mechanics, Lev Landau in 1930 predicted the quantization of the Hall conductance for electrons confined to two dimensions.[23]

Magnetism as a property of matter has been known since pre-historic times.[24] However, the first modern studies of magnetism only started with the development of electrodynamics by Faraday, Maxwell and others in the nineteenth century, which included the classification of materials as ferromagnetic, paramagnetic and diamagnetic based on their response to

magnetization.[25] Pierre Curie studied the dependence of magnetization on temperature and discovered the Curie point phase transition in ferromagnetic materials.[24] In 1906, Pierre Weiss introduced the concept of magnetic domains to explain the main properties of ferromagnets.[26] The first attempt at a microscopic description of magnetism was by Wilhelm Lenz and Ernst Ising through the Ising model that described magnetic materials as consisting of a periodic lattice of spins that collectively acquired magnetization.[24] The Ising model was solved exactly to show that spontaneous magnetization cannot occur in one dimension but is possible in higher-dimensional lattices. Further research such as by Bloch on spin waves and Néel on antiferromagnetism led to the development of new magnetic materials with applications to magnetic storage devices.[24]

Modern many body physics

The Sommerfeld model and spin models for ferromagnetism illustrated the successful application of quantum mechanics to condensed matter problems in the 1930s. However, there still were several unsolved problems, most notably the description of superconductivity and the Kondo effect.[27] After World War II, several ideas from quantum field theory were applied to condensed matter problems. These included recognition of collective modes of excitation of solids and the important notion of a quasiparticle. Russian physicist Lev Landau used the idea for the Fermi liquid theory wherein low energy properties of interacting fermion systems were given in terms of what are now known as Landau-quasiparticles.[27] Landau also developed a mean field theory for continuous phase transitions, which described ordered phases as spontaneous breakdown of symmetry. The theory also introduced the notion of an Order parameter to distinguish between ordered phases.[28] Eventually in 1965, John Bardeen, Leon Cooper and John Schrieffer developed the so-called BCS theory of superconductivity, based on the discovery that arbitrarily small attraction between two electrons can give rise to a bound state called a Cooper pair.[29]



The Quantum Hall effect: Components of the Hall resistivity as a function of the external magnetic field

The study of phase transition and the critical behavior of observables, known as critical phenomena, was a major field of interest in the 1960s.[30] Leo Kadanoff, Benjamin Widom and Michael Fisher developed the ideas of critical exponents and scaling. These ideas were unified by Kenneth Wilson in 1972, under the formalism of the renormalization group in the context of quantum field theory.[30]

The Quantum Hall effect was discovered by Klaus von Klitzing in 1980 when he observed the Hall conductivity to be integer multiples of a fundamental constant.[31] (see figure) The effect was observed to be independent of parameters such as the system size and impurities, and in 1981, theorist Robert Laughlin proposed a theory describing the integer states in terms of a topological invariant called the Chern number. [32] Shortly after, in 1982, Horst Störmer and Daniel Tsui observed the fractional quantum Hall effect where the conductivity was now a rational multiple of a constant. Laughlin, in 1983, realized that this was a consequence of quasiparticle interaction in the Hall states and formulated a variational solution, known as the Laughlin wavefunction. [33] The study of topological properties of the fractional Hall effect remains an active field of research.

In 1987, Karl Müller and Johannes Bednorz discovered the first high temperature superconductor, a material which was superconducting at temperatures as high as 50 Kelvin. It was realized that the high temperature superconductors are examples of strongly correlated materials where the electron-electron interactions play an important role.[34] A satisfactory theoretical description of high-temperature

superconductors is still not known and the field of strongly correlated materials continues to be an active research topic.

In 2009, David Field and researchers at Aarhus University discovered spontaneous electric fields when creating prosaic films of various gases. This has more recently expanded to form the research area of spontelectrics.^[35]

Theoretical

Theoretical condensed matter physics involves the use of theoretical models to understand properties of states of matter. These include models to study the electronic properties of solids, such as the Drude model, the Band structure and the density functional theory. Theoretical models have also been developed to study the physics of phase transitions, such as the Ginzburg–Landau theory, critical exponents and the use of mathematical techniques of Quantum field theory and the renormalization group. Modern theoretical studies involve the use of numerical computation of electronic structure and mathematical tools to understand phenomena such as high-temperature superconductivity, topological phases and gauge symmetries.

Emergence

Theoretical understanding of condensed matter physics is closely related to the notion of Emergence, wherein complex assemblies of particles behave in ways dramatically different from their individual constituents.^[29] For example, a range of phenomena related to high temperature superconductivity are not well understood, although the microscopic physics of individual electrons and lattices is well known.^[36] Similarly, models of condensed matter systems have been studied where collective excitations behave like photons and electrons, thereby describing electromagnetism as an emergent phenomenon.^[37] Emergent properties can also occur at the interface between materials: one example is the lanthanum–aluminate–strontium–titanate interface, where two non-magnetic insulators are joined to create conductivity, superconductivity, and ferromagnetism.

Electronic theory of solids

Main article: Electronic band structure

The metallic state has historically been an important building block for studying properties of solids.[38] The first theoretical description of metals was given by Paul Drude in 1900 with the Drude model, which explained electrical and thermal properties by describing a metal as an ideal gas of then–newly discovered electrons. This classical model was then improved by Arnold Sommerfeld who incorporated the Fermi–Dirac statistics of electrons and was able to explain the anomalous behavior of the specific heat of metals in the Wiedemann–Franz law. [38] In 1913, X–ray diffraction experiments revealed that metals possess periodic lattice structure. Swiss physicist Felix Bloch provided a wave function solution to the Schrödinger equation with a periodic potential, called the Bloch wave. [39]

Calculating electronic properties of metals by solving the many–body wavefunction is often computationally hard, and hence, approximation techniques are necessary to obtain meaningful predictions. [40] The Thomas–Fermi theory, developed in the 1920s, was used to estimate electronic energy levels by treating the local electron density as a variational parameter. Later in the 1930s, Douglas Hartree, Vladimir Fock and John Slater developed the so–called Hartree–Fock wavefunction as an improvement over the Thomas–Fermi model. The Hartree–Fock method accounted for exchange statistics of single particle electron wavefunctions, but not for their Coulomb interaction. Finally in 1964–65, Walter Kohn, Pierre Hohenberg and Lu Jeu Sham proposed the density functional theory which gave realistic descriptions for bulk and surface properties of metals. The density functional theory (DFT) has been widely used since the 1970s for band structure calculations of variety of solids. [40]

Symmetry breaking



Ice melting into water. Liquid water has continuous translational symmetry, which is broken in crystalline ice.

Certain states of matter exhibit symmetry breaking, where the relevant laws of physics possess some symmetry that is broken. A common example is crystalline solids, which break continuous translational symmetry. Other examples include magnetized ferromagnets, which break rotational symmetry, and more exotic states such as the ground state of a BCS superconductor, that breaks U(1)rotational symmetry.[\[41\]](#)

Goldstone's theorem in Quantum field theory states that in a system with broken continuous symmetry, there may exist excitations with arbitrarily low energy, called the Goldstone bosons. For example, in crystalline solids, these correspond to phonons, which are quantized versions of lattice vibrations.[\[42\]](#)

Phase transition

The study of critical phenomena and phase transitions is an important part of modern condensed matter physics.[\[43\]](#) Phase transition refers to the change of phase of a system, which is brought about by change in an external parameter such as temperature. In particular, quantum phase transitions refer to transitions where the temperature is set to zero, and the phases of the system refer to distinct ground states of the Hamiltonian. Systems undergoing phase transition display critical

behavior, wherein several of their properties such as correlation length, specific heat and susceptibility diverge. Continuous phase transitions are described by the Ginzburg-Landau theory, which works in the so-called mean field approximation. However, several important phase transitions, such as the Mott insulator-superfluid transition, are known that do not follow the Ginzburg-Landau paradigm.[44] The study of phase transitions in strongly correlated systems is an active area of research.[45]

Experimental

Experimental condensed matter physics involves the use of experimental probes to try to discover new properties of materials. Experimental probes include effects of electric and magnetic fields, measurement of response functions, transport properties and thermometry. [8] Commonly used experimental techniques include spectroscopy, with probes such as X-rays, infrared light and inelastic neutron scattering; study of thermal response, such as specific heat and measurement of transport via thermal and heat conduction.

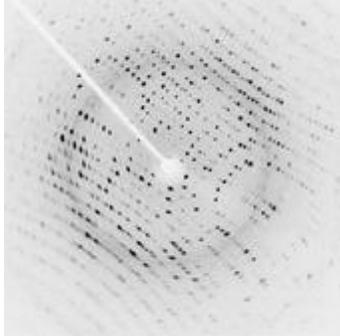


Image of X-ray diffraction pattern from a protein crystal.

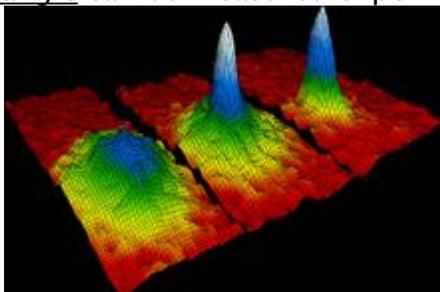
Scattering

Several condensed matter experiments involve scattering of an experimental probe, such as X-ray, optical photons, neutrons, etc., on constituents of a material. The choice of scattering probe depends on the observation energy scale of interest.[46] Visible light has energy on the scale of 1 eV and is used as a scattering probe to measure variations in material properties such as dielectric constant and refractive index. X-rays have energies of the order of 10 keV and hence

are able to probe atomic length scales, and are used to measure variations in electron charge density. neutrons can also probe atomic length scales and are used to study scattering off nuclei and electron spins and magnetization (as neutrons themselves have spin but no charge).[46] Coulomb and Mott scattering measurements can be made by using electron beams as scattering probes,[47] and similarly, positron annihilation can be used as an indirect measurement of local electron density.[48] Laser spectroscopy is used as a tool for studying phenomena with energy in the range of Visible light, for example, to study non-linear optics and forbidden transitions in media.[49]

External magnetic fields

In experimental condensed matter physics, external magnetic fields act as thermodynamic variables that control the state, phase transitions and properties of material systems.[50] Nuclear magnetic resonance (NMR) is a technique by which external magnetic fields can be used to find resonance modes of individual electrons, thus giving information about the atomic, molecular and bond structure of their neighborhood. NMR experiments can be made in magnetic fields with strengths up to 65 Tesla.[51] Quantum oscillations is another experimental technique where high magnetic fields are used to study material properties such as the geometry of the Fermi surface. [52] The quantum hall effect is another example of measurements with high magnetic fields where topological properties such as Chern-Simons angle can be measured experimentally.[49]



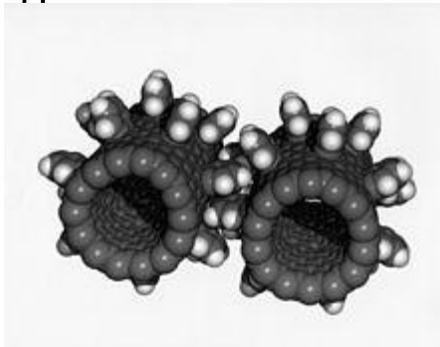
The first Bose-Einstein condensate observed in a gas of ultracold rubidium atoms. The blue and white areas represent higher density.

Cold atomic gases

Cold atom trapping in optical lattices is an experimental tool commonly used in condensed matter as well as Atomic, molecular, and optical physics.^[53] The technique involves using optical lasers to create an interference pattern, which acts as a "lattice", in which ions or atoms can be placed at very low temperatures.^[54] Cold atoms in optical lattices are used as "quantum simulators", that is, they act as controllable systems that can model behavior of more complicated systems, such as frustrated magnets.^[55] In particular, they are used to engineer one-, two- and three-dimensional lattices for a Hubbard model with pre-specified parameters.^[56] and to study phase transitions for Néel and spin liquid ordering.^[53]

In 1995, a gas of rubidium atoms cooled down to a temperature of 170 nK was used to experimentally realize the Bose-Einstein condensate, a novel state of matter originally predicted by S. N. Bose and Albert Einstein, wherein a large number of atoms occupy a single quantum state.^[57]

Applications



Computer simulation of "nanogears" made of fullerene molecules. It is hoped that advances in nanoscience will lead to machines working on the molecular scale.

Research in condensed matter physics has given rise to several device applications, such as the development of the Semiconductor transistor,^[4] and laser technology.^[49] Several phenomena studied in the context of nanotechnology come under the purview of condensed matter physics.^[58] Techniques such as scanning-tunneling microscopy can be used to control processes at the nanometer scale, and have given rise to the study of nanofabrication.^[59] Several condensed matter systems are being studied with potential applications to quantum computation,^[60] including experimental systems like quantum dots, SQUIDs, and theoretical models like the toric code and the quantum dimer model.^[61] Condensed matter systems can be tuned to provide the conditions

of coherence and phase-sensitivity that are essential ingredients for quantum information storage.[59] Spintronics is a new area of technology that can be used for information processing and transmission, and is based on spin, rather than electron transport.[59] Condensed matter physics also has important applications to biophysics, for example, the experimental technique of magnetic resonance imaging, which is widely used in medical diagnosis.[59]

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