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Phase Transitions in Solids from Quantum and Classical Systems

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Description

Phase transitions are fundamental phenomena in material science and condensed matter physics, where a material undergoes a transformation between different states or phases due to changes in external conditions, such as temperature, pressure, or magnetic field. These transitions can occur in a variety of materials and the mechanisms that govern them are studied through both classical and quantum perspectives. In solid-state physics, phase transitions in solids are particularly significant as they affect the material's properties, including its mechanical, electrical and thermal characteristics. Understanding the nature of phase transitions, particularly the differences between quantum and classical systems, provides essential information on behavior of solids under varying conditions.

Classical phase transitions in solids typically involve the transformation between distinct phases, such as from a solid to a liquid (melting) or from one crystalline structure to another (solid-solid transitions). These transitions can be classified into first-order or second-order, based on their thermodynamic properties. A first-order phase transition is characterized by a discontinuous change in properties such as volume, entropy or enthalpy. A common example in solids is the melting of ice into water. In this case, the solid (ice) absorbs heat at a constant temperature and the material changes phase to liquid water. The density of the material, the internal energy and the structure of the material undergo abrupt changes during this process.

Second-order phase transitions are also known as continuous transitions; occur without discontinuities in the thermodynamic quantities. Instead, the behavior of the material changes gradually as the external conditions are altered. One well-known second-order transition in solids is the ferroelectric-to-paraelectric transition in certain crystals. At a critical temperature, the crystal transitions from a ferroelectric phase with spontaneous polarization changes to a paraelectric phase, where the polarization disappears.

Classical phase transitions in solids are often supported by Landau theory, which models phase changes in terms of an order parameter a quantity that describes the symmetry of the material's phase. For example, the order parameter might represent the polarization in ferroelectrics or the magnetization in magnetic materials. In contrast to classical phase transitions, quantum phase transitions occur at absolute zero temperature and are driven by quantum mechanical effects rather than thermal energy. These transitions are often associated with changes in the ground state of a system as a result of the variation in an external parameter, such as pressure or magnetic field. At absolute zero, the system does not possess thermal energy and quantum fluctuations become the dominant influence on the behavior of the material. Quantum phase transitions are particularly relevant in systems where quantum mechanics plays an essential role in the behavior of the material's electrons, spins and other quantum properties. For instance, in certain materials, applying a magnetic field can induce a quantum phase transition from a magnetically ordered phase to a disordered phase, as seen in spin systems.

One of the most well-known examples of quantum phase transitions is found in quantum critical points. A quantum critical point represents a point at which a continuous phase transition occurs at zero temperature and the system undergoes a transition between two different ground states. These transitions are characterized by the divergence of certain physical quantities, such as the specific heat or magnetic susceptibility. Quantum criticality plays an important role in the understanding of strongly correlated electron systems, such as high-temperature superconductors and heavy fermion materials.

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