KVANT FAZA O‘TISHLARI VA ULARNING KRITIK HODISALARDAGI ROLI.

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Annotatsiya: Ushbu maqolada kondensirlangan holatlar fizikasi doirasida kvant faza o‘tishlarining nazariy asoslari, ularning klassik faza o‘tishlaridan farqlari, hamda kritik hodisalar bilan o‘zaro bog‘liqligi ko‘rib chiqiladi. Maqolada renormalizatsiya guruhi, kvant Ginzburg–Landau yondashuvi va asosiy modellar (Ising, Boze–Eynshteyn kondensatsiyasi, suprayo‘qotuvchi–izolyator o‘tishi) misolida tushuntirish beriladi.

Kalit so‘zlar: Kvant faza o‘tishlari, Kritik hodisalar, Landau nazariyasi, Tartib parametri, Kvant kritik nuqta (QCP), Renormalizatsiya guruhi (RG), Ising modeli, Bose–Einstein kondensatsiyasi, Suprayo‘qotuvchi–izolyator o‘tishi, Universallik sinfi, Kvant fluktuatsiyalar, Kondensirlangan holatlar fizikasi.

QUANTUM PHASE TRANSITIONS AND THEIR ROLE IN CRITICAL PHENOMENA

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Abstract: This article examines the theoretical foundations of quantum phase transitions within the framework of condensed matter physics, their differences from classical phase transitions, and their interrelation with critical phenomena. The discussion is illustrated through the concepts of the renormalization group, the quantum Ginzburg–Landau approach, and key models such as the Ising model, Bose–Einstein condensation, and the superconductor–insulator transition.

Keywords: quantum phase transitions, critical phenomena, Landau theory, order parameter, quantum critical point (QCP), renormalization group (RG), Ising model, Bose–Einstein condensation, superconductor–insulator transition, universality class, quantum fluctuations, condensed matter physics.

КВАНТОВЫЕ ФАЗОВЫЕ ПЕРЕХОДЫ И ИХ РОЛЬ В КРИТИЧЕСКИХ ЯВЛЕНИЯХ.

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Аннотация: В данной статье рассматриваются теоретические основы квантовых фазовых переходов в рамках физики конденсированных состояний, их отличия от классических фазовых переходов, а также взаимосвязь с критическими явлениями. В статье даются пояснения на примере ренормализационной группы, квантового подхода Гинзбурга–Ландау и основных моделей (модель Изинга, бозе–эйнштейновская конденсация, переход сверхпроводник–изолятор).

Ключевые слова: квантовые фазовые переходы, критические явления, теория Ландау, параметр порядка, квантовая критическая точка (QCP), ренормализационная группа (RG), модель Изинга, бозе–эйнштейновская конденсация, переход сверхпроводник–изолятор, класс универсальности, квантовые флуктуации, физика конденсированных состояний.

Introduction

Phase transitions occur at points where the macroscopic state of a system changes abruptly, meaning the process in which a material system transforms from one ordered state to another ordered or disordered state [1]. Classical phase transitions are typically governed by thermodynamic quantities such as temperature and pressure; that is, classical phase transitions are associated with thermal fluctuations, whereas quantum phase transitions occur at zero temperature due to quantum fluctuations. As a result, they arise from changes in the parameters of the system’s Hamiltonian.

A classical example is the freezing of water, while a quantum example is the transition of a magnetic insulator from a magnetically ordered to a non-magnetic state at zero temperature [5].

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Theory of Phase Transitions. In Landau theory, the order parameter Ψ indicates the breaking of the system’s symmetry. The order parameter may be zero before the transition and nonzero after the transition. The free energy functional is usually expressed as follows [2]:

$$\mathrm{F}[\Psi] = F_0 + \alpha(T)\Psi^2 + \mathrm{b}\Psi^4 \dots$$

$$\alpha(g) \propto g - g_c$$

Here, α(T) is a coefficient that depends on temperature or another control parameter. The critical exponents α, β, γ, ν, and z describe how physical quantities change near the critical point [3]. For example:

Order parameter: $\Psi \propto |g - g_c|^{\beta}$

Correlation length: $\xi \propto |g - g_c|^{-\nu}$

Dynamic scaling: $\tau \infty \xi^z$

This leads to the principle of universality, meaning that different physical systems can share the same values of critical exponents.

The concept of symmetry breaking plays a central role in this process. For example, in a ferromagnetic material, at high temperatures the spin orientations are random, whereas at low temperatures they become ordered in a single direction.

Quantum Phase Transitions: The main difference in quantum phase transitions is that they are studied within the framework of quantum statistical mechanics using (d + 1)-dimensional theories, which combine spatial and temporal dimensions. For example, they can be considered in a three-dimensional space–time model. The Hamiltonian of the system is:

$$\hat{H}(g) = \widehat{H_0} + g\widehat{H_1}$$

Here, g is the control parameter. At the critical point, when $g = g_c$, the ground state of the system changes abruptly.

At the quantum critical point, thermal fluctuations are replaced by quantum fluctuations, which arise from Heisenberg's uncertainty principle. Near the quantum critical point, the properties of the system are often determined by its universality class, meaning that different materials can share the same mathematical description.

Transverse-field Ising model: The Hamiltonian of the 1D Ising model is:

$$\hat{H} = - J\sum_i \sigma_i^z \sigma_{i+1}^z - h\sum_i \sigma_i^x$$

The critical point occurs when h_c=J

Bose–Einstein condensation: The accumulation of bosonic particles into a single quantum state at zero temperature is also a quantum phase transition, occurring at the critical value of the chemical potential [7].

Superconductor–insulator transition: This occurs in thin films or nanostructures as a result of quantum tunneling of electrons and the Coulomb blockade.

The renormalization group (RG) is a key mathematical tool for explaining these processes, enabling the study of how a system changes at different length scales. The quantum Ginzburg–Landau theory is an extended form of Landau theory that incorporates the time dimension and quantum fluctuations, while the Hubbard model describes strongly correlated electron systems. Using the renormalization group, it is possible to determine how a system changes at all length scales near the critical point. In quantum cases, the renormalization group equations also include the time dimension:

$$\xi_\tau \infty \xi^z$$

The theoretical significance is as follows: quantum phase transitions not only help in understanding new physical phenomena, but also contribute to:
Topological phases,
Quantum computer components [9],
Predicting next-generation superconducting materials.

Conclusion

Quantum phase transitions hold fundamental importance in condensed matter physics, providing a means to explain and predict new phenomena in complex materials. The theoretical study of these processes lays a solid foundation for future technological revolutions. These processes are significant in:

Materials science: essential for predicting and creating new materials such as high-temperature superconductors, spin liquids, and topological insulators.

Quantum computing: collective phenomena occurring in quantum critical systems are used to stabilize quantum bits (qubits) and topological qubits.

Fundamental physics: directly related to universality, symmetry, and quantum field theory.

Thus, the study of quantum phase transitions bridges “micro” and “macro” levels of understanding in physics, develops a deep theoretical model of complex systems, and connects it with experimental results. This makes it one of the most fascinating and promising fields of 21st-century science.

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