MODERN PROBLEMS OF SOLID-STATE PHYSICS

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1. PURPOSES OF MASTERING THE EDUCATIONAL DISCIPLINE

The purposes of mastering the subject are:

to learn about the modern views on the relevant problems in solid-state physics which have been intensively studied recently, on the questions of modern theory and experiments, on the most significant scientific achievements of the last 15-20 years of development of condensed-matter physics.

2. PLACE OF THE EDUCATIONAL DISCIPLINE: *DS – disciplines of specialization.*

The course relies on the subject material of the following courses taught to students majoring in physics and mathematics: Quantum Mechanics*, Theory of Probability, Statistical Physics and Thermodynamics, Theoretical and Experimental Solid-State Physics, Physics of Phase Transitions in Condensed Matter, Magnetic Properties of the Solid State.*

Knowledge of general physics and special physics disciplines is necessary for a successful mastering of the subject. A student needs to be able to work with quantum operators, solve eigenvalue problems, and to know the second quantization formalism, the main types of quantum statistics and thermodynamics. It is necessary to have an understanding of the solid-state physics problems, of crystal lattices, of phonon and electron subsystems in a solid state, of magnetic properties, of phase transitions and the physics of superconductivity.

3. COMPETENCES OF STUDENTS FORMED AS A RESULT OF MASTERING THE EDUCATIONAL DISCIPLINE / EXPECTED RESULTS OF EDUCATION AND COMPETENCES OF A STUDENT UPON MASTERING THE DISCIPLINE

As a result of mastering the discipline, a student should:

1) Know the modern views on the latest achievements in solid-state physics;

2) Be able to formulate and use the latest data on the quantum Hall effect, high-temperature superconductivity, superfluidity and Bose condensation, mesoscopic nanosystems;

3) Be familiar with the modern mathematical methods and physical approaches to experimental and theoretical research of complex strongly correlated systems as well as be able to demonstrate their level of proficiency and awareness when discussing the complex state of modern experimental and theoretical physics.

STRUCTURE AND CONTENTS OF THE SUBJECT MATTER

A basic overview of experiments and theory of the integer and fractional quantum Hall effects as well as the main research results on high-temperature superconductors are provided, the main models claiming to describe the attraction mechanism of charge carriers in HTSCs are reviewed. The main physical effects accompanying superfluid phase transitions in helium-3 and helium-4, the difference between phase transitions in a three-dimensional case and in low-dimensional strongly correlated systems, such as superfluid helium in one-dimensional channels, spin chains and ladders, etc., and Bose condensation in alkaline metals, are considered. The material is followed by a review of history of discovery of the effects and bibliographic references when necessary. A sufficiently detailed presentation of theoretical concepts is provided. On selective subjects, problems are discussed with detailed explanations.

Lecture topics

Topic 1. Integer and fractional quantum Hall effects.
Ordinary Hall effect. Applications. Cases of strong and weak field. The concept of magnetic length. The two-dimensional electron gas. Integer quantum Hall effect. History of discovery. Theoretical explanation. Level quantization in a magnetic field (Landau sublevels). Fractional quantum Hall effect. History of discovery and modern state of experiments. A system of levels in the first Landau band. The concept of Laughlin liquid as a new state of 2D electron gas. Excitations with fractional charge. Theoretical and experimental research of the fractional Hall effect. Wigner crystal – Laughlin liquid phase transitions. Numerical modeling.

Topic 2. High-temperature superconductivity.
Ordinary (low-temperature) superconductors. Historical review. Basic experimental data and theoretical concepts. The BCS and Ginzburg-Landau-Abrikosov-Gorkov theories. Maximum critical temperatures for the electron-phonon mechanism. High-temperature superconductors (HTSCs). History of discovery. Main classes of HTSCs. Features and differences from low-temperature compounds. Main experiments. Influence of pressure, radiation, impurities, external fields on HTSCs. Crystal structure. The Hall effect. Phase diagrams. Antiferromagnetic ordering. Features of vortex states. Features of electronic structure, Fermi surface, dispersion of excitations. Experiments. Symmetry of the superconducting gap, s- and d-coupling. Overview of theoretical HTS models. Models with electron-phonon coupling mechanism.

Topic 3. Theoretical concepts of HTSCs. Non-phonon mechanisms of pairing of charge carriers in HTSCs. Schrieffer’s "Spin bags" and Anderson’s RVB model. Exciton mechanism. Plasmon model. Hubbard model. Main properties and application of HTSCs. The t-J-model and the multiband Emery model for a CuO_2 plane. Theoretical and numerical research of HTS models. Exact diagonalization and Monte Carlo methods. Experimental observations of the Fermi surface via photoemission spectroscopy. Numerical restoration of the generalized density of states, dispersions of quasiparticles and equipotential surfaces from data gained by using the Monte Carlo method.

Topic 4. Superfluidity. Superfluidity of the ^{4}He isotope. Historical sketch. Experimental data. Landau theory of superfluid Bose-liquid. Excitations. Hydrodynamics. ^{3}He isotope – a superfluid fermi-liquid. History of discovery. The Pomeranchuk effect. Three superfluid phases. Theoretical concepts. P-pairing. Anderson-Morel and Balian-Werthamer phases. Mixtures of ^{3}He in ^{4}He. Andreev levels.

Topic 5. Bose condensation in a gas phase. Spin-polarized hydrogen. Experiments in alkaline metals. Ultra-low cooling. Observation of Bose condensate. Three-partial recombination and the “1/6” law. Three-dimensional and two-dimensional gas – the problems of condensation.

Topic 6. Low-dimensional superfluidity. Research of flow of liquid helium in thin porous channels. Mott insulator – superfluid liquid phase transitions. Problem of existence of phase transitions. Criteria. Examples. Bosonic Hubbard model. Superfluidity–Bose-glass–Mott insulator phase diagrams. Accordance with other models. Superflux states.

Topic 7. One-dimensional systems. Criteria of phase transitions for one-dimensional systems. Features of a one-dimensional case. The concept of renormalization group. Theoretical research of critical points within the bosonic Hubbard model.

Topic 8. Spin chains, planes. Anisotropic Heisenberg models. Phase diagrams. Triangular lattice and Kagome lattice. Phase transitions in spin-1 one-dimensional model. Magnetic macromolecules as nanomagnets. Scanning tunnel microscopy.

Lecture schedule

1. Ordinary Hall effect

Ordinary Hall effect. Applications. Cases of strong and weak field. The concept of magnetic length. The two-dimensional electron gas.

2. Integer quantum Hall effect

Integer quantum Hall effect. Level quantization in a magnetic field (Landau sublevels).

3. Fractional quantum Hall effect

A system of levels in the first Landau band. The concept of Laughlin liquid as a new state of two-dimensional electron gas. Excitations with fractional charge.

4. Wigner crystallization

Theoretical and experimental studies of fractional Hall effect. Wigner crystal – Laughlin liquid phase transitions.

5. Low-temperature superconductors

Basic experimental data and theoretical representations.

6. Main classes of HTSCs

Main classes of HTSCs. Features and differences from low-temperature compounds.

7. Structure of HTSCs

Influence of pressure, radiation, impurities, external fields on HTSCs. Crystal structure.

8. Features of telectronic structure

Features of electronic structure. Experiments. Symmetry of the superconducting order parameter, s- and d-pairing.

9. Non-phonon mechanisms of pairing of charge carriers in HTSCs

Non-phonon mechanisms of pairing of charge carriers in HTSCs. Schrieffer’s "Spin bags" and Anderson’s RVB model. Multiband Emery model.

10. Theoretical and numerical research of the HTS models

Exact diagonalization and Monte Carlo methods. Experimental observations of the Fermi surface via photoemission spectroscopy.

11. Superfluidity of the ^{4}He isotope

Experimental data. Landau theory of superfluid Bose-liquid. Excitations. Hydrodynamics.

12. ^{3}He isotope

The Pomeranchuk effect. Three superfluid phases. Theoretical concepts. P-pairing.

13. Bose condensation in a gas phase

Spin-polarized hydrogen. Experiments in alkaline metals. Ultra-low cooling. Observation of the Bose condensate. Three-partial recombination and the "1/6" law.

14. Flow of liquid helium

Mott insulator – superfluid liquid phase transitions. Low-dimensional superfluidity. Problem of existence of phase transitions. Criteria.

15. Criteria of phase transitions

Features of a one-dimensional case. The concept of renormalization group. Theoretical research of critical points within the bosonic Hubbard model.

Control forms: **tests, big semester task, exams**

Examination cards

EXAMINATION CARD NO. 1

1. Ordinary Hall effect. Applications. Cases of strong and weak field.
2. Non-phonon mechanisms of pairing of charge carriers in HTSCs. Magnetic mechanisms. Schrieffer’s "Spin bags."

EXAMINATION CARD NO. 2

1. Integer quantum Hall effect. History of discovery. Level quantization in a magnetic field (Landau sublevels).
2. Review of theoretical HTS models. Models of electron-phonon pairing mechanisms.

EXAMINATION CARD NO. 3

1. Fractional quantum Hall effect. History of discovery and modern state of experiments. A system of levels in the first Landau band.
2. Crystal structure of HTSCs. Phase diagrams. Anti-ferromagnetic ordering.

EXAMINATION CARD NO. 4

1. Wigner crystallization. Wigner crystal – Laughlin liquid phase transitions. Numerical modeling.
2. Ordinary (low-temperature) superconductors. Historical sketch. Basic experimental data and theoretical concepts. The BCS and Ginzburg-Landau-Abrikosov-Gorkov theories. Maximum critical temperatures for the electron-phonon mechanism.

EXAMINATION CARD NO. 5

1. Laughlin liquid as a new state of two-dimensional electron gas. Excitations with fractional charge.
2. High-temperature superconductors (HTSCs). History of discovery. Main classes of HTSCs.

EXAMINATION CARD NO. 6

1. Integer quantum Hall effect. Theoretical explanation. Level quantization in a magnetic field (Landau sublevels).
2. Superfluidity of the ^{4}He isotope. Experimental data.

EXAMINATION CARD NO. 7

1. High-temperature superconductors (HTSCs). Differences from low-temperature superconductors.
2. Three superfluid phases of helium-3. Theoretical concepts. P-pairing. Anderson-Morell and Balian-Werthamer phases.

EXAMINATION CARD NO. 8

1. Review of the theoretical HTS models. Models with electron-phonon pairing mechanism.
2. Bose condensation in a gas phase. Spin-polarized hydrogen. Experiments in alkaline metals. Ultralow cooling.

EXAMINATION CARD NO. 9

1. Fractional quantum Hall effect. History of discovery and current state of experiment. System of levels in the first Landau band.
2. Landau sublevels in a magnetic field. Density of states.

EXAMINATION CARD NO. 10

1. Features of electronic structure, Fermi surface, dispersion of excitations in HTSCs. Experiments.
2. Three superfluid phases in helium-3. P-pairing. Experiments.

EXAMINATION CARD NO. 11

1. Strong correlation HTS models. Concepts of the Hubbard model, *t*-*J*- model, multiband Emery model for a CuO_2 plane.
2. The superfluidity of ^{4}He isotope. Landau theory. Excitations. Explanation of experimental data.

EXAMINATION CARD NO. 12

1. Non-phonon mechanisms of pairing of charge carriers in HTSCs. Magnetic mechanisms. Schrieffer’s "Spin bags" and Anderson’s RVB model.
2. Low-dimensional superfluidity. Bose-Hubbard model.

EXAMINATION CARD NO. 13

1. Crystal structure of HTSCs. Phase diagrams. Features of vortex states.
3. Wigner crystallization. Wigner crystal – Laughlin liquid phase transitions. Numerical modeling.

EXAMINATION CARD NO. 14

1. Integer quantum Hall effect. History of discovery. Level quantization in magnetic field (Landau sublevels).
2. Magnetic and optical traps and ultralow cooling.

EXAMINATION CARD NO. 15

1. Phase diagrams of HTSCs. Anti-ferromagnetic ordering. Influence of pressure, impurities, radiation on the HTS superconducting parameters.
2. ^{3}He isotope – a superfluid fermi-liquid. The Pomeranchuk effect.

EXAMINATION CARD NO. 16

1. Nanotechnology by means of a tunnel microscope, nanomagnets.
2. Ordinary Hall effect. Applications. Case of two bands, concept of strong and weak field.

EXAMINATION CARD NO. 17

1. Fractional quantum Hall effect. History of discovery and current state of experiment. System of levels in the first Landau band.
2. Features of electronic structure, Fermi surface, dispersion of excitations in HTSCs. Experiments.

EXAMINATION CARD NO. 18

1. Fractional quantum Hall effect. Main properties of Laughlin liquid.
2. Bose condensation in a gas phase. Experiments in alkaline metals. Ultra-low cooling. The "1/6" law.

EXAMINATION CARD NO. 19

1. Magnetic macromolecules as nanomagnets. Tunnel microscopy.
2. Main experimental data in favor of non-phonon mechanisms of charge carrier pairing in HTSCs.

EXAMINATION CARD NO. 20

1. ^{3}He isotope – a superfluid fermi-liquid. History of discovery. Pomeranchuk cell.
2. Review of the theoretical HTS models. Models of electron-phonon pairing mechanisms.

EXAMINATION CARD NO. 21

1. The concept of magnetic length. Two-dimensional electron gas - conditions of implementation.
2. Non-phonon mechanisms of pairing of charge carriers in HTSCs. Magnetic Schrieffer model, exciton and plasmon mechanisms.

EXAMINATION CARD NO. 22

1. Integer quantum Hall effect. History of discovery. Theoretical explanation.
2. Review of theoretical HTS models. Models with electron-phonon pairing mechanism. Anderson's arguments.

EXAMINATION CARD NO. 23

1. Difference between the fractional and integer quantum Hall effects.
2. Main classes of HTSCs, crystal structure.

EXAMINATION CARD NO. 24

1. Excitations with fractional charge and incompressibility of the Laughlin liquid.
2. High-temperature superconductors (HTSCs). Differences from low-temperature superconductors and main experiments.

EXAMINATION CARD NO. 25

1. Review of the theoretical HTS models. Models with electron-phonon mechanism of pairing. Anderson's arguments about the impossibility of electron-phonon type of attraction.
2. Bose condensation in a gas phase. Bose condensate observation. Three-partial recombination and the "1/6" law.

EXAMINATION CARD NO. 26

1. Symmetry of the superconducting order parameter in HTSCs, s- and d-pairing. Experimental data.
2. ^{3}He isotope – a superfluid fermi-liquid. History of discovery. The Pomeranchuk effect.

EXAMINATION CARD NO. 27

1. Integer quantum Hall effect. Level quantization in magnetic field (Landau sublevels). Density of states.
2. Laser cooling of atomic gases of alkaline metals.

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