Quantum Simulators and Quantum Matter

Educational subject description sheet

Basic information

Study programme Fizyka **Speciality** INFORMACJA KWANTOWA I SPINTRONIKA **Organizational unit** Faculty of Physics **Study level** Second-cycle programme **Study form** Full-time **Education profile** General academic	**Didactic cycle** 2023/24 **Subject code** 04FIZIKSS.21S.03359.23 **Lecture languages** English **Course type** Obligatory **Block** specialty subjects
Subject coordinator	Ravindra Chhajlany
Lecturer	Ravindra Chhajlany, Tomasz Polak

Period	**Activities and hours**	**Number of ECTS points**
Semester 1	• Lecture: 30, Exam • Classes: 30, Graded credit • Laboratories: 30, Graded credit	7

Goals

Code	Goal
C1	Provide a first introduction to selected basic aspects and methods of many body physics relevant to the description of quantum matter
C2	Discuss the idea of quantum simulators as special purpose quantum computers and various possible implementations of such simulators to describe relevant interesting problems in many body physics
C3	Introduce certain numerical methods useful for tackling research problems in quantum many body physics
C4	Introduce selected topics of current research in the field of quantum simulations

Subject learning outcomes

Code	Outcomes in terms of	Learning outcomes	Examination methods
Knowledge – Student:			
W1	knows the formalism of second quantization as a method to describe many body systems consisting of identical particles	FIZ_K2_W01, FIZ_K2_W02, FIZ_K2_W03	Written exam, Written colloquium, Oral colloquium, Report
W2	knows selected properties of dilute gases of fermions and bosons and their relationship to various phenomena in quantum condensed matter physics, as well as approximate and certain exact methods of describing such systems	FIZ_K2_W01, FIZ_K2_W02, FIZ_K2_W03, FIZ_K2_W04	Written exam, Written colloquium, Oral colloquium, Project, Report
W3	understands the concept and unique features of quantum simulators, especially based on trapped ultra cold gases in optical lattices, as special purpose quantum computers to study many body phenomena	FIZ_K2_W01, FIZ_K2_W02, FIZ_K2_W04, FIZ_K2_W05	Written exam, Written colloquium, Oral colloquium, Project, Report
W4	knows experimental advances in the field of quantum simulations	FIZ_K2_W01, FIZ_K2_W02, FIZ_K2_W04, FIZ_K2_W05	Written exam, Written colloquium, Oral colloquium, Report
W5	knows selected approximate and exact theoretical methods, their advantages and range of applicability, to study quantum many body systems of fermions, bosons, and spins	FIZ_K2_W02, FIZ_K2_W03, FIZ_K2_W04	Written exam, Written colloquium, Oral colloquium, Project, Report
Skills – Student:			
U1	is able to use the language of second quantization in practice to model many body systems of fermions and bosons; is able to analyze quantum spin systems; and qualitatively and quantitatively describe collective phenomena	FIZ_K2_U01, FIZ_K2_U02, FIZ_K2_U03, FIZ_K2_U05, FIZ_K2_U07	Written exam, Written colloquium, Oral colloquium, Project
U2	is able to quantitatively characterize model Hamiltonians describing trapped gases in simple optical lattice systems	FIZ_K2_U01, FIZ_K2_U02, FIZ_K2_U03, FIZ_K2_U05, FIZ_K2_U06, FIZ_K2_U07	Written colloquium, Project
U3	can use various kinds of mean-field methods to solve many body problems	FIZ_K2_U01, FIZ_K2_U02, FIZ_K2_U03, FIZ_K2_U04, FIZ_K2_U05	Written colloquium, Project
U4	can implement and use exact diagonalization routines to study selected systems of fermions, bosons, and spins	FIZ_K2_U01, FIZ_K2_U02, FIZ_K2_U03, FIZ_K2_U04, FIZ_K2_U05	Written colloquium, Project
U5	can study selected simple one dimensional systems using the Density Matrix Renormalization Group	FIZ_K2_U01, FIZ_K2_U02, FIZ_K2_U03, FIZ_K2_U04, FIZ_K2_U05	Written colloquium, Project
U6	can analyze and describe research articles dealing with quantum simulations and many body physics	FIZ_K2_U01, FIZ_K2_U02, FIZ_K2_U06, FIZ_K2_U07	Oral colloquium, Project, Report
Social competences – Student:			
K1	will develop self learning and teamwork skills	FIZ_K2_K01, FIZ_K2_K02, FIZ_K2_K04	Written exam, Written colloquium, Project, Report
K2	will develop critical and independent thinking to evaluate received knowledge	FIZ_K2_K01	Written exam, Written colloquium, Project, Report

Study content

No.	Course content	Subject learning outcomes	Activities
1.	Introduction to, and overview of, quantum simulator platforms of quantum matter	W2, W3, W4, U6, K1, K2	Lecture
2.	Statistical physics of condensed matter systems: basic concepts (identical particles, second quantisation, ideal and weakly interacting gases of bosons and fermions, low dimensional systems, quantum phase transitions)	W1, W2, U1, U2, U6, K1, K2	Lecture, Classes, Laboratories
3.	Optical lattices as artificial solids, engineering of model Hamiltonians with ultracold atoms/molecules, detection in optical lattices	W1, W3, W4, U1, U2, U6, K1, K2	Lecture, Classes, Laboratories
4.	(Generalized) Bose-Hubbard models: phenomenology and selected methods of treatment, quantum simulations with ultra cold gases	W1, W2, W3, W4, W5, U1, U2, U3, U4, U5, U6, K1, K2	Lecture, Classes, Laboratories
5.	(Generalized) Fermi-Hubbard models: phenomenology and selected methods of treatment, quantum simulations with ultra cold gases; quantum magnetism in ultra cold gases	W1, W2, W3, W4, W5, U1, U2, U3, U4, U5, U6, K1, K2	Lecture, Classes, Laboratories
6.	Special advanced topic: artificial gauge fields in quantum simulators: engineering and phenomenology, topological phases in quantum simulators	W1, W2, W3, W4, W5, U1, U2, U3, U4, U5, U6, K1, K2	Lecture, Classes, Laboratories
7.	Current topics of research in quantum many body physics and quantum simulations	W3, W4, W5, U1, U6, K1, K2	Lecture, Classes

Additional information

Activities	Teaching and learning methods and activities
Lecture	Lecture with a multimedia presentation of selected issues, Conversation lecture, Discussion, Problem-based learning
Classes	Problem-based learning, Solving tasks (e.g. computational, artistic, practical), Classes method
Laboratories	Problem-based learning, Solving tasks (e.g. computational, artistic, practical)

Activities	Credit conditions
Lecture	Exam: 60%, Report: 40% Written exam: • 91%-100% of available points; grade: 5 (very good) • 81%-90% of available points; grade: 4+ (good plus) • 71%-80% of available points; grade 4 (good) • 61%-70% of available points, grade 3+ (satisfactory plus) • 50%-60% of available points, grade 3 (satisfactory) • <50% - fail Report: A written term paper on a selected topic (on a research paper, or description of a phenomenon/methodology related to quantum many body physics and/or quantum simulations from a provided list of topics). The quality of the report shall be assessed along with answers on the topic during an oral colloquium. The report shall be graded on the standard scale from 3 to 5.

Activities	Credit conditions
Classes	Colloquium results 60%, class activity - 40% 91%-100% of available points; grade: 5 (very good) 81%-90% of available points; grade: 4+ (good plus) 71%-80% of available points; grade 4 (good) 61%-70% of available points, grade 3+ (satisfactory plus) 50%-60% of available points, grade 3 (satisfactory) <50% - fail Final grade will be the average of the above two categories.
Laboratories	Completion of computational problems during class, i.e. implementation of analytical and numerical calculations of selected problems along with a description of obtained results. Grading system as in previous categories.

Literature

Obligatory

1. Maciej Lewenstein, Anna Sanpera and Verònica Ahufinger, Ultracold Atoms in Optical Lattices: Simulating Quantum Many-Body Systems, Oxford University Press (2012)
2. A. Trabesinger, I. Cirac, P. Zoller et al, Nature Physics Insight – Quantum Simulation, April 2012 Volume 8, No 4, https://www.nature.com/collections/tmqjjbrhcb

Optional

1. A. Altland and B. Simon, Condensed Matter Field Theory, Cambridge University Press (2010)
2. I. Bloch, J. Dalibard, and W. Zwerger. Many-Body Physics with Ultracold Gases, Reviews of Modern Physics 80, 885 (2007)
3. E. Altman et al, Quantum Simulators: Architectures and Opportunities, PRX Quantum 2, 017003 (2021)
4. Andrew J. Daley, Immanuel Bloch, Christian Kokail, Stuart Flannigan, Natalie Pearson, Matthias Troyer & Peter Zoller, Nature 607, 667 (2022)

Calculation of ECTS points

Activities	Activity hours*
Lecture	30
Classes	30
Laboratories	30
Semester paper preparation	30
Preparation for classes	15
Preparation for the exam	30
Preparation for the assessment	15
Student workload	**Hours** 180
Number of ECTS points	**ECTS** 7

* academic hour = 45 minutes

Efekty uczenia się dla kierunku

Kod	Treść
FIZ_K2_K01	The graduate is ready to critically evaluate own knowledge and received content
FIZ_K2_K02	The graduate is ready to recognize the importance of knowledge in solving cognitive and practical problems and seeking expert opinion (also from other scientific disciplines) to overcome difficulties during independent problem solving
FIZ_K2_K04	The graduate is ready to think and act in an entrepreneurial manner
FIZ_K2_U01	The graduate can use their knowledge to formulate and solve complex and unusual problems in the field of physical sciences; select and apply appropriate methods and tools necessary to solve a given problem (including advanced IT techniques), as well as adapt existing methods and tools or develop completely new ones
FIZ_K2_U02	The graduate can find the necessary information in the professional literature, databases and other sources, in particular in scientific journals basic to physics, and perform critical analysis, synthesis and creative interpretation of the collected information
FIZ_K2_U03	The graduate can formulate and test hypotheses related to simple research problems in physics (plan and perform observations, experiments, theoretical calculations or computer simulations and critically evaluate and discuss the results obtained)
FIZ_K2_U04	The graduate can prepare, for various audiences, oral presentations and written studies presenting specialized topics in the field of physical sciences in a communicative way, as well as debate on such topics
FIZ_K2_U05	The graduate can use English in accordance with the requirements set out for level B2+ of the Common European Framework of Reference for Languages, as well as specialist English terminology in the field of physical sciences
FIZ_K2_U06	The graduate can interact with others as part of teamwork and take a leading role in such work; manage team work
FIZ_K2_U07	The graduate can independently determine the directions of further learning and implement a self-education program, learn throughout lifetime using the available international literature and be able to guide others in this regard
FIZ_K2_W01	The graduate knows and understands in-depth selected facts, phenomena, concepts and theories specific to physics and complex relationships between them (constituting advanced general knowledge in the field of physical sciences and representing both key and other selected issues in the field of advanced detailed knowledge in this discipline)
FIZ_K2_W02	The graduate knows and understands in-depth selected research methods and tools as well as mathematical models used in physics
FIZ_K2_W03	The graduate knows and understands in-depth selected computational methods and information technology tools and techniques used to solve complex problems in physics
FIZ_K2_W04	The graduate knows and understands main development trends in the discipline of physical sciences
FIZ_K2_W05	The graduate knows and understands the role of physical sciences in the context of fundamental dilemmas and challenges of modern civilization