Subject card

<table>
<tr><td>Subject name and code</td><td colspan="7">Quantum Information, PG_00182652</td></tr>
<tr><td>Field of study</td><td colspan="7">Physics</td></tr>
<tr><td>Date of commencement of studies</td><td colspan="2">October 2026</td><td colspan="2">Academic year of realisation of subject</td><td colspan="3">2027/2028</td></tr>
<tr><td>Education level</td><td colspan="2">Master’s studies</td><td colspan="2">Subject group</td><td colspan="3">Obligatory subject group in the field of study
Optional subject group
Subject group related to scientific research in the field of study</td></tr>
<tr><td>Mode of study</td><td colspan="2">full-time studies</td><td colspan="2">Mode of delivery</td><td colspan="3">at the university</td></tr>
<tr><td>Year of study</td><td colspan="2">2</td><td colspan="2">Language of instruction</td><td colspan="3">Polish</td></tr>
<tr><td>Semester of study</td><td colspan="2">3</td><td colspan="2">ECTS credits</td><td colspan="3">7.0</td></tr>
<tr><td>Learning profile</td><td colspan="2">academic</td><td colspan="2">Assessment form</td><td colspan="3">exam</td></tr>
<tr><td>Conducting unit</td><td colspan="7"></td></tr>
<tr><td rowspan="2">Name and surname of lecturer (lecturers)</td><td colspan="2">Subject supervisor</td><td colspan="5">dr hab. Michał Studziński</td></tr>
<tr><td colspan="2">Teachers</td><td colspan="5"></td></tr>
<tr><td rowspan="3">Lesson types</td><td>Lesson type</td><td>Lecture</td><td>Tutorial</td><td>Laboratory</td><td>Project</td><td>Seminar</td><td>SUM</td></tr>
<tr><td>Number of study hours</td><td>45.0</td><td>30.0</td><td>15.0</td><td>0.0</td><td>0.0</td><td>90</td></tr>
<tr><td colspan="7">E-learning hours included: 0.0</td></tr>
<tr><td rowspan="2">Learning activity and number of study hours</td><td>Learning activity</td><td colspan="2">Participation in didactic classes included in study plan</td><td colspan="2">Participation in consultation hours</td><td>Self-study</td><td>SUM</td></tr>
<tr><td>Number of study hours</td><td colspan="2">90</td><td colspan="2">0.0</td><td>85.0</td><td>175</td></tr>
<tr><td>Subject objectives</td><td colspan="7">Familiarizing students with the use of quantum-system properties for the transmission, processing, and computation of information, and developing the theoretical and numerical skills necessary for further independent study in the field as well as for participation in student research projects.</td></tr>
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Learning outcomes	Course outcome	Subject outcome	Method of verification
	[FIZMU2_W01] has advanced knowledge of general physics and in-depth knowledge of various areas of physics; knows the history of the development of physics and its importance for the progress of exact and natural sciences, cognition of the world and social development	The student knows and understands the evolution of information theory from its classical formulation to the quantum framework. The student understands the similarities and differences between the two theories and is aware of the limitations inherent in each approach.	[SW4] test/exam - oral or written [SW1] oral statement/ conversation/discussion
	[FIZMU2_W04] knows the principle of operation of measuring systems and research equipment specific to the area of physics related to the selected specialization or knows advanced methods of theoretical and mathematical physics	The student knows the basic experimental implementations used to create quantum circuits and quantum protocols, understands the limitations of the methods discussed, and is aware of the need for their further development.	[SW4] test/exam - oral or written [SW1] oral statement/ conversation/discussion
	[FIZMU2_W05] knows the theoretical foundations of computational methods and IT techniques used to model and simulate physical systems	The student knows the theoretical foundations of computational methods and information-technology techniques used for modelling and simulating simple systems in quantum information, in particular quantum algorithms and protocols.	[SW4] test/exam - oral or written [SW2] presentation/project/paper/ report
	[FIZMU2_W06] has knowledge of the current directions of development of physics and fundamental dilemmas of modern civilization	The student possesses knowledge of current directions in the development of quantum information and understands its role in key challenges of contemporary civilization, such as secure communication, advances in computational technologies, and the impact on a data-driven economy.	[SW4] test/exam - oral or written [SW1] oral statement/ conversation/discussion [SW2] presentation/project/paper/ report
	[FIZMU2_U09] can work independently or in a team	The student is able to carry out project and research tasks in quantum information independently and to collaborate effectively within a team when solving theoretical and computational problems.	[SU1] oral statement/conversation/ discussion [SU2] presentation/project/paper/ report [SU4] test/exam - oral or written [SU8] observation of student's independent or team work
	[FIZMU2_K01] knows the limitations of his own knowledge and skills; can formulate questions precisely; understands the need for further education and other	The student is aware of the ongoing quantum revolution. The student understands and can articulate, both orally and in writing, the cognitive, economic, and social implications of the development of quantum technologies. The student is also familiar with the limitations and challenges that must be addressed for the further advancement of quantum technologies.	[SK1] oral statement/conversation/ discussion [SK2] presentation/project/paper/ report [SK4] test/exam - oral or written
	[FIZMU2_W03] knows experimental, observational and numerical techniques to plan and perform a complex physics experiment or computer simulation	The student knows fundamental experimental and observational techniques used in quantum-information research and can indicate how they are applied in planning and conducting complex physical experiments. The student knows and understands numerical methods for simulating quantum systems, including software tools that enable the design and execution of computer simulations of quantum processes.	[SW4] test/exam - oral or written [SW2] presentation/project/paper/ report

Course outcome	Subject outcome	Method of verification
[FIZMU2_K02] is aware of the conclusive role of experiment in the verification of physical theories; is aware of the scientific method in the accumulation of knowledge	The student understands the decisive role of experimentation in confirming and falsifying theories in quantum information and can indicate examples of experiments that have established the foundations of this field. The student is aware of the importance of the scientific method in the acquisition of knowledge in quantum physics, can critically assess research results, and distinguish evidence-based conclusions from speculation.	[SK1] oral statement/conversation/ discussion [SK4] test/exam - oral or written
[FIZMU2_U01] is able to apply the scientific method in solving physical problems, conducting experiments and reasoning	The student is able to independently formulate and prove propositions using techniques appropriate to the level of the quantum information course. The student can engage in group discussions on quantum information theory, is aware of the validity of their own arguments, and can defend them by presenting a well-reasoned scientific argument.	[SU1] oral statement/conversation/ discussion [SU2] presentation/project/paper/ report [SU4] test/exam - oral or written
[FIZMU2_W02] has in-depth knowledge in mathematics as well as mathematical and computational methods, necessary to solve physical problems of high complexity and in-depth in the selected area of physics	The student knows and understands the basic mathematical formalism and numerical methods used in quantum information theory and is aware of the limitations of the methods discussed. The student is aware of and understands the necessity of continuing to explore new and more efficient formalisms and methods in quantum information.	[SW4] test/exam - oral or written [SW1] oral statement/ conversation/discussion

Subject contents

BASIC CONCEPTS
Postulates of quantum mechanics. Dirac notation. Density matrix. Quantum measurement. Quantum channel and Kraus decomposition. Concept of the qubit and the Bloch sphere.
Separable and entangled states.

EXAMPLES OF QUANTUM PROTOCOLS
BB84 protocol, E91 protocol, dense coding protocol, and quantum teleportation (including experimental realization).

QUANTUM CIRCUITS
Concept of a quantum gate and quantum circuit with basic examples. Universality of a set of quantum gates with examples. Elements of quantum complexity theory. Examples of protocols implementing quantum computations (DeutschJozsa, Shor algorithm and its cryptographic implications).

ELEMENTS OF QUANTUM COMPUTATION AND ERROR CORRECTION
Types of errors. Quantum error correction, threshold theorem, Kitaev codes. The problem of quantum supremacy (boson sampling). Classical simulability of quantum computations. Examples of hybrid quantumclassical computational methods (VQE, QAOA). Discussion of classical simulations that challenge the quantum nature of the D-Wave computer.

ELEMENTS OF QUANTUM CRYPTOGRAPHY
Basics of classical cryptography (symmetric and asymmetric protocols, typical cryptographic attacks). Quantum key distribution (BB84, E91, BBM92 with a security proofoutline). Quantum random-number generation. Device-independent quantum cryptography. Elements of quantum hacking. Overview of basic experimental implementations.

PHYSICAL IMPLEMENTATIONS (SELECTED TOPICS)

General layout of a single-qubit gate: Rabi oscillations. Dephasing. Relaxation and coherence times T1 and T2
Superconducting qubit. Josephson junction. Effective Hamiltonian of a superconducting qubit. Main sources of noise. Transmon. Single-qubit gates, two-qubit gates, measurement. Spin qubit. Quantum dot. Coulomb blockade. Single-qubit gates, two-qubit gates, measurement.

<table>
<tr><td>Prerequisites and co-requisites</td><td colspan="2">Knowledge of the fundamentals of quantum mechanics together with the basics of algebra and mathematical analysis, as well as knowledge of the fundamentals of classical information theory.</td></tr>
<tr><td>Assessment methods and criteria</td><td colspan="2"><table><tr><th>Subject passing criteria</th><th>Passing threshold</th><th>Percentage of the final grade</th></tr><tr><td>homework assignments and projects</td><td>51.0%</td><td>35.0%</td></tr><tr><td>written exam</td><td>51.0%</td><td>65.0%</td></tr></table></td></tr>
<tr><td rowspan="3">Recommended reading</td><td>Basic literature</td><td>Nielsen and Chuang, Quantum Computation and Quantum information, Cambridge University Press;

Michel Le Bellac, Wstęp do informatyki kwantowej, Państwowe Wydawnictwo Naukowe (in Polish);
John Watrous, Lecture notes, https://cs.uwaterloo.ca/~watrous/QC-notes/;
Selected scientific articles provided by the instructor(s).</td></tr>
<tr><td>Supplementary literature</td><td>N.David Mermin, Quantum Computer Science (An introduction), Cambridge University Press

Daniel A. Lidar and Todd A. Brun, Quantum Error Correction, Cambridge University Press

Thomas M. Cover, Joy A. Thomas, Elements of Information Theory, Wiley-Interscience

Paul Skrzypczyk and Daniel Cavalcanti, Semidefinite Programming in Quantum Information Science, IOP Publishing</td></tr>
<tr><td>eResources addresses</td><td></td></tr>
<tr><td>Example issues/ example questions/ tasks being completed</td><td colspan="2">-Explain the difference between the description of a pure state and a mixed state using the density matrix.

-Prove that the Hadamard and CNOT gates form a universal set for quantum circuits.

-Simulate the process of quantum teleportation in Python/QuTiP and calculate the fidelity of the transmitted state.

-Explain the idea of the threshold theorem in the context of building quantum computers.

-Implement in Qiskit a simple error-correction code (e.g., the 3-qubit bit-flip code) and analyze its effectiveness for different error probabilities.

-Calculate the mutual information for a two-qubit Bell state.

-Discuss the signification of boson sampling in the context of quantum supermacy.</td></tr>
<tr><td>Work placement</td><td colspan="2">Not applicable</td></tr>
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