UAB
Universitat Autònoma de Barcelona

Quantum Information

Code: 100182
ECTS Credits: 6

2025/2026

Degree	Type	Year
Physics	OT	4

Contact

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Teachers

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Teaching groups languages

You can view this information at the end of this document.

Prerequisites

It is advisable to have a good command of algebra, especially of vector spaces and, preferably, of complex Euclidean spaces. Notions of quantum mechanics. of course. are recommended, but the course is quite self-contained. Knowledge of quantum optics is complementary and recommended, but not essential.

Objectives and Contextualisation

The course offers an introduction to the modern perspective of quantum mechanics and its paradigms. With today's available technology, many of the most paradoxical quantum effects have moved beyond academic curiosities and have become powerful resources that form the basis of quantum technologies, with numerous and surprising practical applications. Some of these applications will be presented in this course: teleportation, dense coding, quantum cryptography, quantum computation and simulation, etc.
The course is designed for physicists, but also for mathematicians, computer scientists, and engineers. Since it is a self-contained course, it includes an introduction to the fundamentals of quantum mechanics, classical information theory, classical cryptography and computation, to allow students to understand the contributions of their quantum counterparts.
The course also has an applied component closely linked to quantum optics. It includes an introduction to the semiclassical and quantum theory of light-matter interaction, as well as a description of the principles and their implementation in concrete physical systems for quantum communication and quantum computation/simulation.
The goal of the course is not only to provide an overview of the advances in quantum information but also to equip students with the basic tools necessary to pursue graduate-level education in this field, should they be interested.

Competences

- Apply fundamental principles to the qualitative and quantitative study of various specific areas in physics
- Be familiar with the bases of certain advanced topics, including current developments on the parameters of physics that one could subsequently develop more fully
- Carry out academic work independently using bibliography (especially in English), databases and through collaboration with other professionals
- Communicate complex information in an effective, clear and concise manner, either orally, in writing or through ICTs, and before both specialist and general publics
- Formulate and address physical problems identifying the most relevant principles and using approximations, if necessary, to reach a solution that must be presented, specifying assumptions and approximations
- Make changes to methods and processes in the area of knowledge in order to provide innovative responses to society's needs and demands.
- Take account of social, economic and environmental impacts when operating within one's own area of knowledge.
- Use critical reasoning, show analytical skills, correctly use technical language and develop logical arguments
- Use mathematics to describe the physical world, selecting appropriate tools, building appropriate models, interpreting and comparing results critically with experimentation and observation
- Using appropriate methods, plan and carry out a study or theoretical research and interpret and present the results
- Work independently, have personal initiative and self-organisational skills in achieving results, in planning and in executing a project
- Working in groups, assume shared responsibilities and interact professionally and constructively with others, showing absolute respect for their rights.

Learning Outcomes

1. Apply quantum measurement in the context of information theory.
2. Apply the axioms of quantum mechanics to problems of information processing.
3. Apply the concept of quantum measurement (Von Neumann or generalized) to simple problems of optimization, discrimination, estimation and quantum communication.
4. Apply the matrix formulation of quantum mechanics to quantum protocols and algorithms.
5. Carry out a project that relates the concepts of quantum information and computation studied with current innovative issues and present the results.
6. Carry out academic work independently using bibliography (especially in English), databases and through collaboration with other professionals
7. Communicate complex information in an effective, clear and concise manner, either orally, in writing or through ICTs, in front of both specialist and general publics.
8. Contrast classical information theory with that of quantum theory.
9. Demonstrate an understanding of both Von Neumann's measurement and generalized measurements.
10. Demonstrate an understanding of EPR states and formulate Bell's inequalities.
11. Demonstrate an understanding of physical implementations for one- and two-qubit quantum logic gates.
12. Demonstrate an understanding of Schmidt's decomposition of bipartite quantum states.
13. Demonstrate an understanding of Shannon's concept of entropy, channel capacity and corresponding theorems.
14. Demonstrate an understanding of the BB84 and Eckert91 protocols for quantum cryptography.
15. Demonstrate an understanding of the quantum algorithms of Deutsch-Józsa, Shor and Grover.
16. Demonstrate an understanding of the quantum versions of the said concepts and theorems.
17. Describe the bases of light-matter interaction necessary to understand the physical implementations of cryptography and quantum computing.

18. Describe the concept of quantum entanglement state, its characterization and its use in quantum information.
19. Describe the main implementations of quantum computing.
20. Describe the similarities and differences between cryptography and classical computation, their quantum versions and their relationship to the physical principles underlying the latter.
21. Differentiate between pure quantum states and statistical mixture.
22. Establish the main protocols of quantum cryptography.
23. Formulate the statistical interpretation of mixed quantum states.
24. Identify situations in which a change or improvement is needed.
25. Identify the social, economic and environmental implications of academic and professional activities within one's own area of knowledge.
26. Relate the fundamentals of quantum information with the principal current physical implementations of cryptography and quantum computing.
27. Solve problems on the characterization of entanglement in quantum states by Schmidt decomposition.
28. Use critical reasoning, show analytical skills, correctly use technical language and develop logical arguments
29. Use the concept of state mixture to solve simple problems with open systems.
30. Use the quantum theory of light-matter interaction to understand the characteristics of quantum light sources.
31. Use the semiclassical theory of light-matter interaction to understand the cooling and trapping of particles, in addition to the implementation of single-qubit logic gates.
32. Work independently, take initiative itself, be able to organize to achieve results and to plan and execute a project.
33. Working in groups, assume shared responsibilities and interact professionally and constructively with others, showing absolute respect for their rights.

Content

Part I (Theoretical aspects)

1. Introduction
    - Quantum physics and information.
    - Axioms of quantum mechanics.
2. Statistical states and samples
    - The qubit.
    - The density matrix.
    - Bipartite systems.
    - The Schmidt decomposition.
    - Statistical interpretation of the mixed states.
3. Measurements and temporal evolution
    - von Neumann measurements.
    - General measures.
    - Neumark theorem.
    - Quantum channels.
4. Entanglement and its applications
    - States EPR.
    - Dense coding.
    - Teleportation of states.

5. Classical and quantum information

- Introduction to probability.
- Information. Shannon entropy and mutual information.
- Communication. The symmetrical binary channel. Capacity of a channel.
- Shannon theorems.
- Difference between classical and quantum information.
- von Neumann entropy. Shumacher's theorem.
- Holevo information. Accessible information and Holevo limit.

6. Quantum Computing

- Turing machines.
- Circuits and complexity classification.
- The quantum computer.
- Quantum logic gates.
- Deutsch-Josza and Simon algorithms.
- Unstructured Search: Grover's algorithm
- RSA encryption method.
- Factorization: Shor's algorithm.

Part II (Quantum Technologies)

1. Brief review of the interaction between light and matter

- Semiclassic theory of light-matter interaction.
  - The two-level atom.
  - AC-Stark splitting.
  - Rabi oscillations.
  - Light's dipole force.
- Quantum theory of light-matter interaction.
  - States of the quantum e.m. field.
  - The Jaynes-Cummings model.
  - The problem of decoherence.

2. Quantum communication.

- Quantum cryptography: BB84 and Ekert91 protocols.
- Bell Inequalities.
- Generation of individual photons
- Propagation of individual photons.
- Detection of individual photons.

3. Quantum computation and simulation.

- Neutral atoms (ground state and Rydberg) in dipolar traps
- Cavity Quantum Electrodynamics.
- Ions in Paul traps.
- Superconducting qubits.

Activities and Methodology

Title	Hours	ECTS	Learning Outcomes
Type: Directed			

Exercises lectures	16	0.64	3, 2, 4, 1, 7, 21, 25, 24, 27, 33, 29, 30, 31
Theory lectures	33	1.32	13, 14, 15, 10, 11, 12, 9, 16, 8, 18, 17, 19, 20, 22, 23, 25, 24, 28, 26
Type: Autonomous			
Exercises to deliver	20	0.8	3, 2, 4, 1, 7, 21, 6, 5, 25, 24, 27, 32, 33, 29, 30, 31
Solving exercises	40	1.6	3, 2, 4, 1, 21, 28, 27, 32, 29
Study of the theoretical background	35	1.4	13, 14, 15, 10, 11, 12, 9, 16, 8, 18, 17, 19, 20, 22, 23, 26

The theoretical classes are presented using Keynote/PowerPoint slides. Some lectures or seminars on specific course topics will be delivered by researchers in the field of Quantum Information. These seminars will generally be held in English.
Problem-solving classes are usually conducted on the blackboard and involve working through the most significant exercises, whose statements will be made available to students via the Virtual Campus.

There will be two assignments for the theoretical part and one for the quantum technologies section. Their goal is to deepen, consolidate, and extend students' understanding of the topics and results covered throughout the course. These assignments may include more complex or extensive problems and questions. They must be submitted periodically throughout the course on previously agreed dates. These activities are designed to encourage independent work.

All materials - problem sets, additional teaching materials, detailed solutions to selected exercises, and course-related announcements - will be made available to students via the Virtual Campus.

Annotation: Within the schedule set by the centre or degree programme, 15 minutes of one class will be reserved for students to evaluate their lecturers and their courses or modules through questionnaires.

Assessment

Continous Assessment Activities

Title	Weighting	Hours	ECTS	Learning Outcomes
A multiple-choice test on quantum tecnologies	20	1	0.04	14, 10, 11, 17, 19, 20, 22, 25, 24, 26, 30, 31
Attendance and participation in specialized seminars	5	0	0	5, 25, 24, 28, 33
Delivery of exercises (autonomous work)	30	0	0	3, 2, 1, 7, 13, 15, 12, 9, 16, 8, 18, 21, 6, 23, 25, 24, 28, 32, 33
Evaluation exam of theoretical concepts	45	2	0.08	3, 2, 4, 1, 7, 13, 15, 12, 9, 16, 8, 18, 21, 23, 28, 27, 29
Retaken exam of theoretical concepts	45	2	0.08	3, 2, 4, 1, 7, 13, 15, 12, 9, 16, 8, 18, 21, 23, 28, 27, 29
Retaken test on quantum tecnologies	20	1	0.04	14, 10, 11, 17, 19, 20, 22, 26, 30, 31

Evaluation will be based on the following components:

1. A theoretical concepts test, accounting for 45%
2. A multiple-choice test on quantum technologies, accounting for 20%
3. Submission of homework assignments completed independently during the course, accounting for 30%
4. Attendance and active participation in specific seminars held during the course, accounting for 5%

Students who have completed at least 66% of the total evaluation activities will be eligible to take resit exams for activities 1 and 2.
Students who have only completed activities 3 and 4 will be considered not evaluable.

Bibliography

The Virtual Campus provides students with notes on the subject in pdf format and a copy of the Keynote/Powerpoint of the course. The following bibliography is recommended for further information:

Basic

Theory

- J. Preskill. Lectures notes on Quantum Computation. Es pot obtenir gratuïtament a la direcció: http://www.theory.caltech.edu/people/preskill/ph229.
- M.A. Nielsen; S.L. Chuang. Quantum Computation and Quantum Information. Cambridge Univ. Press, Cambridge 2000.
- S.M. Barnett, Quatum Information, Oxford University Press, 2009.

• A. Peres. Quantum Theory: Concepts and Methods. Kluwer, Dordrecht 1995.
• D. Applebaum. Probability and Information. Cambridge Univ. Press, Cambridge 1996.
• D. Boumeester; A. Eckert; A. Zeilinger. The Physics of Quantum Information. Springer 2000.
• D. Heiss. Fundamentals of Quantum Information. Springer 2002.

Exercises

- Steeb, Willi-Hans, and Yorick Hardy. *Problems and solutions in quantum computing and quantum information*. World Scientific Publishing Company, 2018.
- C. P. Williams; S. Clearwater. Exploration in Quantum Computing. Springer 1998

Advanced

• R. A. Bertlmann; A. Zeilinger. Quantum (Un)speakables. Springer 2002.
• A. Ekert; R. Jozsa. Quantum Computation and Shor's Factoring Algorithm. Rev. Mod. Phys. 68 (1996) 733.

- T.A. Cover; J.A Thomas, Elements of Information Theory, John Wiley 2006.

Software

IBM quantum composer

Groups and Languages

Please note that this information is provisional until 30 November 2025. You can check it through this link. To consult the language you will need to enter the CODE of the subject.

Name	Group	Language	Semester	Turn
(PAUL) Classroom practices	1	English	second semester	afternoon
(TE) Theory	1	English	second semester	morning-mixed