Universitat Autònoma de Barcelona

2022/2023

Quantum Information

Code: 100182
ECTS Credits: 6

Degree	Type	Year	Semester
2500097 Physics	OT	4	2

Contact

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Use of Languages

Principal working language: english (eng)
Some groups entirely in English: Yes
Some groups entirely in Catalan: No
Some groups entirely in Spanish: No

Other comments on languages

Some lectures will be delivered in english by invited researchers.

Teachers

Gael Sentís Herrera

Alessio Celi

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 is an introduction to the current vision of quantum mechanics and its paradigms. With the technology we have today, many of the most paradoxical quantum effects have ceased to be an academic curiosity and have become powerful resources that will be the basis for numerous and surprising practical applications in the not-too-distant future. This course presents some of them: teleportation, dense coding, quantum cryptography and computation, and so on. The course is aimed at physicists, but is also of interests for mathematicians, computer scientists and engineers. We aim at providing a self-contained course and therefore it will contain an introduction to the fundamentals of quantum mechanics, classical information theory, clasisical cryptography and computation, in order to be able to evaluate the new contributions of the corresponding quantum versions. The subject also has an applied aspect intimately linked to quantum optics. An introduction to the semiclassical and quantum theory of light-matter interaction will be made, and physical implementations of quantum communication and computation will be described. The aim of the course is not only to give a description of the advances that have taken place in quantum information, but also to provide the student with the basic tools to be able to continue his or her postgraduate training in this field, if this is of interest to the student.

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. 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.
7. Contrast classical information theory with that of quantum theory.
8. Demonstrate an understanding of EPR states and formulate Bell's inequalities.
9. Demonstrate an understanding of Schmidt's decomposition of bipartite quantum states.
10. Demonstrate an understanding of Shannon's concept of entropy, channel capacity and corresponding theorems.
11. Demonstrate an understanding of both Von Neumann's measurement and generalized measurements.
12. Demonstrate an understanding of physical implementations for one- and two-qubit quantum logic gates.
13. Demonstrate an understanding of the BB84 and Eckert91 protocols for quantum cryptography.
14. Demonstrate an understanding of the quantum algorithms of Deutsch-Józsa, Shor and Grover.
15. Demonstrate an understanding of the quantum versions of the said concepts and theorems.
16. Describe the bases of light-matter interaction necessary to understand the physical implementations of cryptography and quantum computing.
17. Describe the concept of quantum entanglement state, its characterization and its use in quantum information.
18. Describe the main implementations of quantum computing.
19. Describe the similarities and differences between cryptography and classical computation, their quantum versions and their relationship to the physical principles underlying the latter.
20. Differentiate between pure quantum states and statistical mixture.
21. Establish the main protocols of quantum cryptography.

22. Formulate the statistical interpretation of mixed quantum states.
23. Identify situations in which a change or improvement is needed.
24. Identify the social, economic and environmental implications of academic and professional activities within one's own area of knowledge.
25. Relate the fundamentals of quantum information with the principal current physical implementations of cryptography and quantum computing.
26. Solve problems on the characterization of entanglement in quantum states by Schmidt decomposition.
27. Use critical reasoning, show analytical skills, correctly use technical language and develop logical arguments
28. Use the concept of state mixture to solve simple problems with open systems.
29. Use the quantum theory of light-matter interaction to understand the characteristics of quantum light sources.
30. 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.
31. Work independently, take initiative itself, be able to organize to achieve results and to plan and execute a project.
32. Working in groups, assume shared responsibilities and interact professionally and constructively with others, showing absolute respect for their rights.
33. Carry out academic work independently using bibliography (especially in English), databases and through collaboration with other professionals

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 (Physical Implementation)

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.

Methodology

The course is structured into theory lectures, exercises lectures, and continuous assessment activities.

The theory lectures are in keynote/powerpoint presentation format. There will be some classes/seminars on some course topics that will be presented by researchers in the field of Quantum Information. These seminars will generally be in English.

The exercises lectures are usually made on the blackboard and consist of solving the most significant problems, the statements of which are made available to students through the Virtual Campus.

There will be 4 deliveries in the theoretical part and 2 in the implementation part. The objective is to deepen, consolidate and extend the students' knowledge about aspects and results explained throughout the course. Thus, the deliveries may contain problems and issues of greater complexity and extension. These should be delivered periodically throughout the course and on previously agreed dates. The aim of these activities is to encourage autonomous work.

All the material: lists of problems, additional teaching material, detailed resolution of some exercises, as well as news related to the course, are made available to the students through 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.

Activities

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

Assessment

The evaluation consists of the following activities

1. An exam of theoretical concepts, with a weight of 45%.
2. A multiple-choice test on implementation aspects, weighing 20%.
3. Delivery of exercises carried out autonomously throughout the course, with a weight of 30%.
4. Attendance and active participation in the specific seminars to be held during the course, with a weight of 5%.

Students who have been evaluated in at least 66% of the total activities may take the retaken exam for activities 1 and 2. A student who has only completed activities 3 and 4 will be considered non-evaluable.

Assessment Activities

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

Retaken exam of theoretical concepts	45	2	0.08	3, 2, 4, 1, 6, 7, 10, 14, 9, 11, 15, 17, 20, 22, 27, 26, 28
Retaken test on implementation concepts	20	1	0.04	13, 8, 12, 16, 18, 19, 21, 25, 29, 30

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