UAB Universitat Autònoma de Barcelona

Quantum Optics

Code: 100180
ECTS Credits: 6

2024/2025

Degree	Type	Year
2500097 Physics	OT	4

Contact

Name: Veronica Ahufinger Breto

Email: veronica.ahufinger@uab.cat

Teaching groups languages

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

Prerequisites

There are no prerequisites. However, it is recommended to have passed Quantum Physics I and II.

Objectives and Contextualisation

The aim of this course is to provide students with the fundamental concepts of Quantum Optics. In particular, we will study in detail light-matter interaction at a microscopic level using semiclassical and quantum theory. These two approaches are at the basis of very active research fields such as laser physics, coherent control of matter waves, cooling and trapping of atoms, and quantum information. Throughout the course we will provide connections to all these fields and discuss recent research results.

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. Analyse the physics of two and three-level atomic systems interacting with one or two laser fields, respectively.
2. Calculate the dressed states of a two-level system interacting with an electromagnetic field.
3. Calculate the interaction dynamics of a two-level system coupled to a single mode of the electromagnetic field.
4. Carry out a project that relates the concepts of quantum optics studied with current innovative issues and present the results.
5. 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.
6. Deduce the dipolar force of light and describe the radiation pressure.
7. Describe the Hanbury-Brown and Twiss experiment.
8. Describe the concept of spatial and temporal coherence of light.
9. Describe the phenomenon of spontaneous emission.
10. Describe the techniques for handling the internal and external states of atoms using light-matter interaction and its applications to quantum engineering.
11. Describe the techniques to control light propagation and their applications to quantum memories.
12. Formulate the properties of different quantum states of the electromagnetic field.
13. Identify situations in which a change or improvement is needed.
14. Identify the social, economic and environmental implications of academic and professional activities within one's own area of knowledge.
15. Model the cavity quantum electrodynamics
16. Pose and solve the equations for the coherent evolution of a system of two atomic levels interacting with a laser field using the Schrödinger's equation.
17. Solve problems of light-matter interaction in semiclassical theory using the density matrix technique.
18. Use critical reasoning, show analytical skills, correctly use technical language and develop logical arguments
19. Use the normal variables to describe the electromagnetic field and its quantisation.
20. Within the electric dipole and rotating wave approximations, calculate the dynamics of two- and three-level systems interacting with a classical or a quantum field.
21. Work independently, take initiative itself, be able to organize to achieve results and to plan and execute a project.
22. Working in groups, assume shared responsibilities and interact professionally and constructively with others, showing absolute respect for their rights.
23. Carry out academic work independently using bibliography (especially in English), databases and through collaboration with other professionals

Content

1. Introduction

Overview of classical, semiclassical and quantum theories of light-matter interaction. Atomic structure.

2. Semiclassical theory of light-matter interaction

Basic processes of light-matter interaction. Einstein's rate equations. Schrödinger equation. Two-level atom under the rotating wave approximation. AC-Stark splitting. Rabi oscillations. Mollow's triplet. Autler-Townes doublet. Light shifts. Dipole force. Density-matrix formalism for a two level atom. Optical Bloch equations. Dressed states. Rapid adiabatic passage. Density-matrix formalism for a three level atom. Coherent Population Trapping. Electromagnetically Induced Transparency. Stimulated Raman Adiabatic Passage.

3. Quantum theory of light-matter interaction

3. 1. Light's description

Classical electrodynamics. Quantization of the e.m. field. Quantum states of the free e.m. field. Fock states. Vacuum state. Coherent states. Squeezed states. Homodyne detection. Optical coherence and Hanbury-Brown and Twiss experiment. Wigner function and other representations of quantum states of light.

3. 2. Light-matter interaction

Jaynes-Cummings model. Dressed atom. Quantum Rabi oscillations. Collapses and revivals. Cavity quantum electrodynamics. Weisskopf-Wigner theory of spontaneous emission.

Activities and Methodology

Title	Hours	ECTS	Learning Outcomes
Type: Directed			
Exercises classes	16	0.64	1, 2, 3, 6, 7, 8, 9, 10, 11, 12, 15, 16, 17, 19, 20
Lectures (Theory classes)	33	1.32	1, 2, 3, 6, 7, 8, 9, 10, 11, 12, 15, 16, 17, 19, 20
Type: Supervised			
Deliveries	1.5	0.06	5, 18, 21, 23
Oral presentation	1.5	0.06	4, 5, 18, 21, 22, 23
Type: Autonomous			
Preparation and study of the theory concepts	46	1.84	1, 4, 5, 6, 7, 8, 9, 10, 11, 12, 15, 18, 19, 21, 22, 23
Solving exercises	46	1.84	2, 3, 4, 5, 16, 17, 18, 20, 21, 22, 23

In the lectures, the course contents will be discussed in detail always encouraging the students participation by raising questions.

In the exercises classes, it is intended that the students participate actively asking questions and contributing to the resolution of the exercises during the class.

The required autonomous work of the student in this course includes the study of theoretical concepts as well as the preparation and solution of the exercises.

The course also features supervised activities consisting of the delivery of exercises and an oral presentation of a current topic of Quantum Optics, which will be done in group.

The material for both the lectures and for the exercises classes will be provided through the UAB Virtual Campus of this subject.

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
Deliveriy of activities	15%	0	0	4, 5, 18, 21, 23
First partial exam	35%	3	0.12	1, 3, 6, 7, 8, 9, 10, 11, 16, 17, 20
Oral presentation	15%	0	0	5, 13, 14, 18, 21, 22, 23
Retaking exam first partial	35%	0	0	1, 2, 3, 6, 7, 8, 9, 10, 11, 12, 15, 16, 17, 19, 20
Retaking exam second partial	35%	0	0	1, 2, 3, 6, 7, 8, 9, 10, 11, 12, 15, 16, 17, 19, 20
Second partial exam	35%	3	0.12	2, 9, 12, 15, 19, 20

Continuous assessment

The final mark of the subject will be obtained as follows:

- 35% : Mark of the first partial exam.
- 35% : Mark of the second partial exam.
- 15% : Mark of the activities to deliver.
- 15% : Mark of the oral presentation.

In order to apply these percentages, the mark in each of the partial exams should be equal or above 3.5 from 10. If the mark of one or both partial exams is below 3.5, the student has to do a retaking exam of the part of the subject failed with mark below 3.5. If a student has passed the subject but he/she would like to improve the mark of the written exams, he/she can do a retaking exam and the final mark of the subject will be calculated using the percentages shown above with the mark obtained in the retaking exam. If a student does not attend any of the exams or only attends one of the partial exams and does not attend the retaking exam, his/her mark will be "No avaluable".

Single assessment

Students who have opted for the single assessment mode will have to take a final test consisting of an exam of the contents of the first partial. Afterwards, they will have to do an exam of the contents of the second partial where they will have to solve a series of exercises similar to those that have been worked on in the exercises sessions and also some more theoretical questions. These tests will take place on the same day, time and place as the second partial exam of the continuous assessment modality.

The student's mark will be the weighted average of the two previous activities, where each of the two exams account for 42.5% of the mark, and of the mark of the oral presentation, which will have been presented during the course on the day established for all students, and which represents 15% of the mark.

If the mark of each of the final tests does not reach 3.5 (out of 10) or if the final mark of the subject does not reach 5 (out of 10), the student has another opportunity to pass the subject by means of a retaking exam that will be held on the same day, time and place as the retaking exam of the continuous assessment modality. In this exam, 85% of the grade, corresponding to the final tests can be recovered. The oral presentation is not recoverable.

Bibliography

- Daniel A. Steck, *Quantum and Atom Optics* (2007); Oregon Center for Optics and Department of Physics. Oregon University

http://atomoptics.uoregon.edu/~dsteck/teaching/quantum-optics/quantum-optics-notes.pdf

- P. Meystre and M. Sargent, *Elements of Quantum Optics*, Springer-Verlag, 4th edition, 2007.

- M. O. Scully and M.S. Zubairy, *Quantum Optics*, Cambridge U. P., 1997.

- D. F. Walls and G.J. Milburn, *Quantum Optics*, Springer-Verlag, 2nd edition, 2008.

- C. C. Gerry and P. Knight, *Introductory Quantum Optics*, Cambridge University Press, 2005.

- C. Cohen-Tannoudji, J. Dupont-Roc and G. Grynberg, *Atom-Photon Interactions: Basic processes and applications*. John Wiley & Sons, 1998.

- C. Cohen-Tannoudji, J. Dupont-Roc and G. Grynberg, *Photons and Atoms: Introduction to Quantum Electrodynamics*. John Wiley & Sons, 1997.

- H. J. Metcalf and P. van der Straten, *Laser Cooling and Trapping*, Springer-Verlag, 1999.

- S. Haroche and J.M. Raimond. *Exploring the Quantum: Atoms, Cavities and Photons.* Oxford University Press, 2006.

- J. M. Raimond, M.Brune and S. Haroche, Reviews of Modern Physics 73, 565 (2001).

Software

No specific software is required.

Language list

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