

**COURSE DATA****DATA SUBJECT**

Code: 34276
Name: Quantum optics
Cycle: Undergraduate Studies
ECTS Credits: 6
Academic year: 2025-26

STUDY (S)

Degree	Center	Acad. year	Period
1105 - Degree in Physics	Facultat de Física	4	Second quarter

SUBJECT-MATTER

Degree	Subject-matter	Character
1105 - Degree in Physics	Complements of Physics	ELECTIVES

COORDINATION

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SUMMARY

Descriptors: Quantum theory of light, photons, coherent states, squeezed light, non-classical light, light-atom interaction, photodetection, theory of laser.

Objectives: This course aims for students to achieve a basic understanding of the quantum nature of light and the interaction of this (in the optical domain of the electromagnetic spectrum, which excludes frequencies above and below the X-rays to microwaves) with matter, mainly with atoms and molecules. After quantifying the field, we study the coherent states of the electromagnetic field and discusses their properties. Discussed below are the basic processes of interaction (spontaneous emission, stimulated emission and absorption). After the study photodetection (capitally essential to understand the quantum nature of light), paying particular attention to the so-called «non-classical states» of radiation, such as compressed states (squeezed states), studying how they can be generated. It also addresses an introduction to quantum entanglement and its implications for quantum optics.

Besides all this, is also an aim to understand the fundamental aspects of the semiclassical theory of light-matter interaction (in which the field is treated classically) with the intention of obtaining the fundamental



equations of semiclassical laser theory (equations Maxwell-Bloch). Studies of this phenomena include nonlinear dynamics of lasers in the emission (such as deterministic chaos) which are of transverse interest.

Relation to previous courses: Quantum optics is based on the compulsory courses in optics, electromagnetism and quantum mechanics. The skills taught in this course have not been treated in any other head, except the lens, which is the theory of laser-balance equations of Einstein and quantum mechanics, which is (partially) some aspects which are developed further in quantum optics.

PREVIOUS KNOWLEDGE

RELATIONSHIP TO OTHER SUBJECTS OF THE SAME DEGREE

There are no specified enrollment restrictions with other subjects of the curriculum.

OTHER REQUIREMENTS

It is recommended basic knowledge of classical electromagnetism, quantum mechanics and classical optics. All these skills are acquired studying the corresponding subjects of the degree in physics.

COMPETENCES / LEARNING OUTCOMES

1105 - Degree in Physics

Ability to collect and interpret relevant data in order to make judgements.

Basic & applied Research: acquire an understanding of the nature and ways of physics research and of how physics research is applicable to many fields other than physics, e.g. engineering; be able to design experimental and/or theoretical procedures for: (i) solving current problems in academic or industrial research; (ii) improving the existing results.

Communication Skills (written and oral): Being able to communicate information, ideas, problems and solutions through argumentation and reasoning which are characteristic of the scientific activity, using basic concepts and tools of physics.

Foreign Language skills: Have improved command of English (or other foreign languages of interest) through: use of the basic literature, written and oral communication (scientific and technical English), participation in courses, study abroad via exchange programmes, and recognition of credits at foreign universities or research centres.

Knowledge and understanding of the fundamentals of physics in theoretical and experimental aspects, and the mathematical background needed for its formulation.

Learning ability: be able to enter new fields through independent study, in physics and science and technology in general.

Literature Search: be able to search for and use physical and other technical literature, as well as any other sources of information relevant to research work and technical project development.



Modelling & Problem solving skills: be able to identify the essentials of a process / situation and to set up a working model of the same; be able to perform the required approximations so as to reduce a problem to an approachable one. Critical thinking to construct physical models.

Physics general culture: Be familiar with the most important areas of physics and with those approaches which span many areas in physics, or connections of physics with other sciences.

Problem solving: be able to evaluate clearly the orders of magnitude in situations which are physically different, but show analogies, thus allowing the use of known solutions in new problems .

Students must be able to apply their knowledge to their work or vocation in a professional manner and have acquired the competences required for the preparation and defence of arguments and for problem solving in their field of study.

Students must be able to communicate information, ideas, problems and solutions to both expert and lay audiences.

Students must have acquired knowledge and understanding in a specific field of study, on the basis of general secondary education and at a level that includes mainly knowledge drawn from advanced textbooks, but also some cutting-edge knowledge in their field of study.

Students must have developed the learning skills needed to undertake further study with a high degree of autonomy.

Students must have the ability to gather and interpret relevant data (usually in their field of study) to make judgements that take relevant social, scientific or ethical issues into consideration.

To know how to apply the knowledge acquired to professional activity, to know how to solve problems and develop and defend arguments, relying on this knowledge.

DESCRIPTION OF CONTENTS

1. Semiclassical theory of light-matter interaction

1. Introduction. The two-level atom
2. Interaction Hamiltonian
3. Evolution equations. The rotating-wave approximation
4. Rabi oscillations
5. The dressed atom
6. Pulses
7. Dissipation. The density matrix. Optical Bloch equations
8. The refractive index
9. Three-level atoms. Two-photon, Raman and hyper-Raman processes

Seminars: Semiclassical laser theory

1. The ring cavity two-level laser



2. Amplification in a two-level medium
3. The laser: single-mode emission
4. The Lorenz-Haken model
5. Linear stability analysis
6. Spontaneous pulsations and routes to chaos

2. Quantization of the free electromagnetic field

1. Canonical quantization of a harmonic oscillator. Creation and annihilation operators
2. The free em field: potentials and gauge invariance
3. The standard em field Lagrangian. Scheme for the standard quantization
4. Canonical quantization of a mode in a Fabry-Perot resonator
5. Free em field Hamiltonian
5. Electric and magnetic fields operators. Linear and angular momentum operators
6. Time evolution pictures

3. Photons and the quantum vacuum

1. Number or Fock states: photons
2. The electric field in a Fock state
3. The em vacuum. Quantum fluctuations
4. The Casimir effect

4. Coherent states

1. Quasi-classical states of the electromagnetic field
2. Expansion of coherent states in the Fock basis
3. The displacement operator
4. Physical properties of the coherent states
5. Mathematical properties of the coherent states

5. Squeezed states

1. The field quadrature operators



2. Balanced homodyne detection
3. Introduction to quantum squeezing
4. The squeezing operator
5. Parametric down conversion
6. Squeezed states

6. Quantum theory of light-atom interaction

1. Electric-dipole Hamiltonian
2. Elementary processes
3. Spontaneous emission. Weisskopf-Wigner theory
4. Decay. Spontaneous emission within cavities
5. Atomic level energy shift. The Lamb shift.
6. Mass renormalization

7. The Jaynes-Cummings model

1. Introduction. The Rabi model
2. The Jaynes-Cummings model
3. Trapped ion driven by classical light
4. Solving the Schrödinger equation
5. Atomic properties evolution
6. Field properties evolution
7. Experimental observations

8. Quantum coherence and photodetection

1. Introduction
2. Semi-classical theory of photodetection and coherence
3. Quantum theory of photodetection and coherence

9. Entanglement

1. The concept of entanglement in quantum mechanics



2. Pure entangled states: characterization and quantification
3. Einstein-Podolski-Rosen (EPR) and their attack to quantum theory
4. Bell inequalities
5. The beam splitter as an entangling element

WORKLOAD

PRESENCIAL ACTIVITIES

Activity	Hours
Theory	60,00
Total hours	60,00

NON PRESENCIAL ACTIVITIES

Activity	Hours
Attendance at other activities	0,00
Individual or group project	20,00
Independent study and work	50,00
Preparation of lessons	0,00
Preparation for assessment activities	0,00
Resolution of case studies	20,00
Total hours	90,00

TEACHING METHODOLOGY

This course has two types of classes. The first one corresponds to the theoretical or theoretical-practices in which it is reforced, as much as possible, the participation of students. This is the most common type of class in this subject (52 of the 60 hour period). During these classes the teacher presents an orderly and self-contained (to the extent possible) the contents of the seven chapters of the course.

The second kind of classes corresponds to the seminars and these are subdivided into two: half of the seminars are theoretical (the difference with the recently described classes is that it is not intended to be as complete and self-contained). The aim is that students learn to follow a more relajados contents of a portion of matter, especially enhancing intuition and concentrating efforts on the study of net models. The other half of the seminars are practical since in them aprendecomo are built and used the software needed to complete the planned simulations.

EVALUATION

The evaluation consists of:

- 1) **Examination.** Its grade (N1) can reach up to 10 points (the maximum score).



The exam evaluates the understanding of the theoretical-conceptual aspects and the formalism of the subject, the ability to apply them to problem solving and the ability to criticize the results obtained. In any case, the correct argumentation and adequate justification will be valued. There will be an exam in each call.

2) **Continuous evaluation.** Its grade (N2) can reach up to 10 points (the maximum score).

The evaluation is based on the realization, individually or in groups, of numerical simulations, reports, summaries, resolution of problems and questions, and other activities. The result of the evaluation may take into account written deliverables, oral presentations and defenses, as well as short written tests.

In the first call, the grade for the course will be $0.6*N1+0.4*N2$. In the second call, the grade for the course will be $\max\{N1,0.6*N1+0.4*N2\}$. In both summonses, it is a necessary condition to pass the course (5 or more out of 10) that N1 exceeds the minimum grade of 3.5 out of 10. Otherwise, the final grade will be N1.

REFERENCES

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- C. Cohen-Tannoudji, J. Dupont-Roc i G. Grynberg, Photons and atoms. Introduction to Quantum Electrodynamics (John Wiley and Sons, 1989)
- H. Haken, Light (vols. 1 i 2) (North Holland, 1985)
- L. Mandel i E. Wolf, Optical coherence and Quantum Optics (Cambridge University Press, 1995)
- L. Allen and J.H. Eberly, Optical resonance and two-level atoms (Dover, 1987)
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- W. Vogel i D.-G. Welsch, Lectures on quantum optics (Akademie Verlag, 1994)
- M.O. Scully i M.S. Zubairy, Quantum Optics (Cambridge University Press, 1997)