COURSE DATA

DATA SUBJECT

Code: 43292
Name: Quantum field theory I
Cycle: Master's Degree
ECTS Credits: 6
Academic year: 2026-27

STUDY (S)

Degree	Center	Acad. year	Period
2150 - Master's degree in Advanced Physics	Facultat de Física	1	First quarter

SUBJECT-MATTER

Degree	Subject-matter	Character
2150 - Master's degree in Advanced Physics	Introduction to theoretical physics	ELECTIVES

COORDINATION

CIERI - LEANDRO JAVIER

SUMMARY

In **Quantum Field Theory I** students will delve into the foundations of the mathematical formalism essential for the study of particle physics. We will explore the Klein-Gordon, Dirac, photon, and Proca fields, and learn how to calculate cross-sections and decay widths using the powerful Feynman rules.

In addition to examining the elementary processes of quantum electrodynamics (QED) and the concept of renormalization, students will acquire the ability to calculate all available scattering amplitudes in QED at lowest order in perturbation theory for 2->2 processes, among others. This course will provide a solid foundation for understanding the fundamental interactions of elementary particles, the crucial concept of gauge symmetry, and its profound implications in modern physics.

PREVIOUS KNOWLEDGE

RELATIONSHIP TO OTHER SUBJECTS OF THE SAME DEGREE

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

OTHER REQUIREMENTS

COMPETENCES / LEARNING OUTCOMES

2150 - Master's degree in Advanced Physics

Analizar una situación compleja extrayendo cuales son las cantidades físicas relevantes y ser capaz de reducirla a un modelo parametrizado.

Conocer la fenomenología de las partículas elementales. Conocer cómo se clasifican las partículas elementales y las interacciones fundamentales. Comprender la relación entre el microcosmos y la formación del macrocosmos.

Conocer los dispositivos experimentales. Conocer la experimentación con la materia elemental y manejar los resultados.

Evaluar la validez de un modelo o teoría propuesto por otros miembros de la comunidad científica.

Exponer y defender públicamente el desarrollo, resultados y conclusiones de su trabajo en el área de la Física.

Ostentar la preparación para tomar decisiones correctas en la elección de tareas y en su ordenación temporal en su labor investigadora y/o profesional.

Ser capaz de gestionar información de distintas fuentes bibliográficas especializadas utilizando principalmente bases de datos y publicaciones internacionales en lengua inglesa.

Students should apply acquired knowledge to solve problems in unfamiliar contexts within their field of study, including multidisciplinary scenarios.

Students should be able to integrate knowledge and address the complexity of making informed judgments based on incomplete or limited information, including reflections on the social and ethical responsibilities associated with the application of their knowledge and judgments.

Students should communicate conclusions and underlying knowledge clearly and unambiguously to both specialized and non-specialized audiences.

DESCRIPTION OF CONTENTS

1. Introduction: the need for a quantum theory of fields

We will present the motivations and needs for a relativistic quantum field theory and the corresponding historical aspects.

2. Classical Klein-Gordon and Dirac fields

We will learn how to construct the Klein-Gordon and Dirac field equations, essential for describing relativistic particles, and understand their fundamental properties through their Lagrangians, currents, and conserved charges.

3. Gauge symmetry in Abelian and non-Abelian theories

Gauge symmetry is a fundamental principle in particle physics, underlying the fundamental interactions of nature. We will discuss the fundamental principle of gauge, how interaction terms arise, and how gauge fields naturally emerge, in our case the photon. We will also address how the scenario is modified in non-Abelian theories of SU(N) and provide a brief historical overview.

4. Quantization of the Klein-Gordon field

In this chapter, we will explore the quantization of the free Klein-Gordon field, starting from its corresponding Lagrangian density. We will learn how to promote coordinates to operators in Hilbert space and detail the process of second quantization or canonical quantization. Using the harmonic oscillator as an introduction, we will define the charge of a quantum state and express it in terms of its corresponding quantum operators. Finally, we will discuss the first indications of the need for renormalization in quantum field theory.

5. Quantization of the Dirac Field

Following a similar structure to that used for the Klein-Gordon field, we will address the quantization of the Dirac field. We will focus particularly on the crucial differences in the commutation relations of the fields, which distinguish this case from that of Klein-Gordon.

6. Quantization of Photon and Maxwell-Proca Fields: Unveiling Degrees of Freedom and Gauge Choice

In this crucial chapter, we will explore the fascinating quantization of photon and Maxwell-Proca fields. We will learn how the expansion in plane waves, along with a strategic choice of gauge, allows us to unveil the mysteries of these fundamental particles.

We will directly address the challenges inherent in the quantization of these fields, including the identification of physical and spurious degrees of freedom. We will see how the choice of gauge influences this process and how Fermi's ingenious solution helps us overcome one of the most important obstacles.

Finally, we will culminate our journey with the powerful Gupta-Bleuler quantization method. We will analyze in detail how gauge fixing is transformed in the context of fields that have undergone second quantization.

7. Interacting Quantum Fields

We will explore interacting quantum fields, analyzing how the quantization rules and the different representations are modified in the presence of interactions. We will introduce the evolution matrix and the essential knowledge to understand the S matrix, a key piece in scattering theory.

8. The S-matrix and Wick's Theorem

This material explores the S-matrix, a key tool in quantum field theory for calculating transition probabilities, focusing on its perturbative construction using the Dyson series expansion and Wick's theorem. Additionally, a concrete example in ¿¿¿ theory is presented, showing how to obtain the first terms of the S-matrix, deduce the Feynman rules, and construct the corresponding diagrams.

9. Feynman Rules in Quantum Electrodynamics (QED): Unveiling Fundamental Interactions

In this crucial chapter, we will explore Feynman rules, a powerful tool for describing and calculating interaction processes in quantum electrodynamics (QED). We will learn to identify and apply these rules to construct Feynman diagrams, intuitive visual representations of the interactions between charged particles and photons.

We will address the fundamental notion of the propagator in QED, comparing it with the propagator in Klein-Gordon theory to highlight the key differences. Additionally, we will delve into the concept of causality in quantum field theory, examining how Feynman rules ensure consistency with special relativity and the causal structure of spacetime.

10. Calculation of Amplitudes and Cross Sections in QED: From Diagrams to Physical Results

In this section, we will put theory into practice by calculating scattering amplitudes to first order in QED for processes with two initial and two final particles. We will learn to master the crossing rules, which allow us to connect particles between initial and final states, and to exploit symmetries to simplify calculations.

Furthermore, we will discover how to obtain squared matrix elements directly from Feynman diagrams, streamlining the process. We will also delve into the calculation of a one-loop matrix element, a key introduction to the concepts of renormalization in QED.

11. Introduction to Renormalization

This chapter explores the concept of renormalization in quantum field theory (QFT), focusing on quantum electrodynamics (QED) and quantum chromodynamics (QCD). Renormalization is crucial for handling the divergences that arise in perturbative QFT calculations due to high-energy or short-distance contributions.

WORKLOAD

PRESENCIAL ACTIVITIES

Activity	**Hours**
Theory	40,00
Seminar	3,00
Other activities	3,00
Total hours	**46,00**

NON PRESENCIAL ACTIVITIES

Activity	**Hours**
Attendance at other activities	0,00
Individual or group project	21,00
Independent study and work	0,00
Preparation of lessons	43,00
Preparation for assessment activities	0,00
Resolution of case studies	40,00
Total hours	**104,00**

TEACHING METHODOLOGY

MD1 - Standar theory lecture

MD2 - Discussion of articles (readings).

MD3 - Problem solving

MD4 - Problems

MD8 - Conference of experts

EVALUATION

The course evaluation is based on:

- A written examination based on the lectures and practical sessions, covering the learning outcomes and specific objectives of the course (70%).

- Continuous evaluation of the student during theory and practice classes, including participation, completing in-class exercises and solving proposed problems (30%). The final grade is approved with 5/10, and a minimum grade of 4.0/10 in the exam is required to average with the continuous assessment grade.

- There are no differences between the first and second call of the final exam. Please note that all written exercises must be submitted before the first final exam call.

REFERENCES

- M.E. Peskin and D.V. Schroeder, "An Introduction to Quantum Field Theory", 1995.
- C. Itzykson and J.B. Zuber, "Quantum Field Theory", McGraw-Hill, 1980.
- J.D. Bjorken and S.D. Drell, "Relativistic Quantum Fields", McGraw-Hill, 1965.
- S. Weinberg, "The Quantum Theory of Fields", Cambrigde University Press, 1995.
- Francis Halzen and Alan D. Martin, "Quarks and Leptons: An Introductory Course in Modern Particle Physics", Wiley; First Edition (16/01/1991).
- David Griffiths, "Introduction to Elementary Particles", Wiley-VCH; 2nd edition (October 2008).

- J. Reinhardt and Walter Greiner, "Field Quantization", Springer; First Edition (01/01/1996).