FDD3026 Open Quantum Systems 7.5 credits

Öppna kvantsystem

This is a translation of the Swedish, legally binding, course syllabus.

If the course is discontinued, students may request to be examined during the following two academic years

Establishment

Course syllabus for FDD3026 valid from Autumn 2022

Grading scale

P, F

Education cycle

Third cycle

Specific prerequisites

No special prerequisites.

Language of instruction

The language of instruction is specified in the course offering information in the course catalogue.

Intended learning outcomes

1. After completing the course the students will be familiar with the concepts of pure states, mixed states, observables, density matrices, entanglement and von Neumann entropy of a reduced density matrix as a measure of entanglement. The students will be able to describe orally and/or in writing the EinsteinPodolski-Rosen experiment as an example of quantum correlations than can be given a classical interpretation (local hidden variables) and Bell theorem as an example of quantum correlations that cannot be given a classical interpretation (no local hidden variables). The students will be aware of the Local operations and classical communication (LOCC) paradigm, and of the quantum no cloning theorem.

2. After completing the course the students will be familiar with the concepts of Kraus operators, quantum Markov process, Lindblad equation, Lindblad operators and Feynman-Vernon functionals, and will know the number of parameters describing a general open quantum system evolution.

3. After completing the course the students will be aware of Feynman-Vernon functionals as encoding decoherence and dissipation, and be able to derive the Feynman-Vernon functional using operator techniques. The students will also be able to derive Lindblad equation from the Feynman-Vernon functional as a memory-less limit.

4. After completing the course the students will be aware of simulation techniques for open quantum systems without or with memory including the Lindblad equation, the quantum jump method, the stochastic Schrodinger equations and the hierachical equations of motion method (HEOM). The students will be able to compare the different methods to each other, and to decide which is more appropriate in a given application.

5. After completing the course the students will be able to consider in quantitative detail an atom evolving in interaction with the quantum electrodynamic field as an instance of an open quantum system interacting with an environment.

6. After completing the course the students will be able to discuss Einstein-Podolsky-Rosen correlations, non-local measurements and quantum causality in the language of relativistic quantum theory, and will be able to describe quantum non-demolition verification of non-local states.

7. After completing the course the students will understand the concept of quantum teleportation, and will be able to describe the principles of currently leading experimental realization and implementations.

8. After completing the course the students will understand decoherence through interaction with the quantum electrodynamic field as emission of brehmstrahlung and will be able to describe on a qualitative level the evolution of the decoherence functional for a quantum test body interacting with the quantized electromagnetic field.

Course contents

Chapters in Breuer & Petruccione are referred to as BP1, BP2, etc.
Lectures 1-6 contain a compressed version of the planned Master level course, sufficient to following the PhD course proper. Lectures 7-18 contain the actual PhD level course.
Lecture 1: Overview of the course contents. Repetition of the basics of quantum mechanics. Pure states as rays in Hilbert space. Observables and Hermitian operators. Schrödinger picture, Heisenberg picture and interaction picture. Schrödinger equation. Time evolution of pure states and unitary operators. Mixed states and density matrices. The von Neumann

equation describing the time evolution of a density matrix. BP2.
Lecture 2: Basics of quantum information processing. Entanglement. Von Neumann entropy as a measure of entanglement. Einstein-Podolski-Rosen experiment as an example of quantum correlations than can be given a classical interpretation (local hidden variables). Bell theorem as an example of quantum correlations that cannot be given a classical interpretation (no local hidden variables). The Local operations and classical communication (LOCC) paradigm. The quantum no cloning theorem (without proof).
Lecture 3: Basics of open quantum system dynamics. The time evolution of a reduced density matrix. Kraus operators. Number of parameters describing a general open quantum system evolution. The case of quantum Markov processes. Lindblad equation and Lindblad operators. BP3 and BP4.
Lecture 4: Decoherence and dissipation. Feynman-Vernon influence functionals. Derivation of the Feynman-Vernon influence functional using path integrals (without evaluating the actual integrals). Kernels in the Feynman-Vernon functionals are operator correlation functions in the environment. Derivation of Lindblad equation as a memory-less limit of the Feynman-Vernon approach.
Lecture 5: Practical and theoretical limits to the Feynman-Vernon approach. Overview of the alternatives if the open system itself is a harmonic oscillator. If that is not the case nor a Lindblad equation limit is appropriate, the open quantum system dynamics has to be solved numerically.
Lecture 6: The Jaynes-Cumming and the spin-boson models. Quantum memory effects. A survey of simulation techniques for open quantum systems with memory. The complexity of open quantum system dynamics in even simple set-ups at low enough temperature. BP7 & BP10.
Lecture 7: Evolution of open quantum systems as PDEs and as integro-differential equations.
Stochastic simulation methods. The quantum jump method. Stochastic Schrödinger equations.
BP7.
Lecture 8. The hierachical equations of motion method (HEOM). [extra material]
Lecture 9. Driven harmonic oscillators. Comparison between different numerical methods. BP7.
Lecture 10. Applications to quantum optics systems I. Continuous measurements in quantum electrodynamics. The microscopic Hamiltonian. Incomplete measurements. BP8.
Lecture 11. Applications to quantum optics systems II. Dark states. An atom evolving in interaction with the quantum electrodynamic field as an environment. BP8.
Lecture 12. Application to quantum optics III. Strong field interaction and the Floquet picture. BP8.
Lecture 13. Relativistic quantum theory on the formal level. Schwinger-Tomonaga equation. States as functionals of spacelike hypersurfaces. Foliations of space-time. The measurement of local observables. Relativistic state reduction. BP11.
Lecture 14.
EPR correlations. Non-local measurements and causality. Entangled quantum probes. Quantum state verification. Quantum non-demolition verification of non-local states. BP11.
Lecture 15.
Quantum teleportation. Teleportation and Bell-state measurement. A survey of xperimental realization and implementations. BP11 and additional material.
Lecture 16.
Density matrix theory for quantum electro-dynamics. Field equations and correlation functions. The influence functional (Feynman-Vernon functional). BP12.
Lecture 17.
Vacuum-to-vacuum amplitudes. Decoherence by the emission of brehmstrahlung. The de-

coherence functional. Evolution of the decoherence functional for a quantum test body interacting with the quantized electromagnetic field. BP12.
Lecture 18.
Decoherence of many-particle states. Limits to quatum information processing from the interactions with photons. Bp12.

Examination

- EXA1 - Examination, 7.5 credits, grading scale: P, F

Based on recommendation from KTH's coordinator for disabilities, the examiner will decide how to adapt an examination for students with documented disability.

The examiner may apply another examination format when re-examining individual students.

The examination will be in three parts: (1) a standard written exam covering the same material as the master-level course (lectures 1-6); (2) correctly executed three homeworks on the material specific to the PhD-level lecture (lectures 7-18) ; (3) an oral exam.

Other requirements for final grade

Passed written exam, correctly excuted homeworks, passed oral exam.

Ethical approach

- All members of a group are responsible for the group's work.
- In any assessment, every student shall honestly disclose any help received and sources used.
- In an oral assessment, every student shall be able to present and answer questions about the entire assignment and solution.