UNIVERSITÀ DI TRENTO
Department of Physics
Doctoral Programme in Physics

# SYLLABUS Academic year 2023/2024

(ANNEX TO THE TRAINING PROGRAMME)

## MANDATORY COURSE

| Teacher | Course | Credits | Hours |
| --- | --- | --- | --- |
| G. Lattanzi / A. Brunello | Scientific Writing, Speaking and Storytelling | 3 | 24 |

## GROUP 1 – CHARACTERISING COURSES

| Teacher | Course | Credits | Hours |
| --- | --- | --- | --- |
| G. Baldi, * (coordinator) | Advanced Techniques in Experimental Physics | 3 | 24 |
| M. Calandra, F. Pederiva | Multiscale modeling | 3 | 24 |
| G.A.Prodi (coordinator) | Data Analysis Methods for Physics | 3 | 24 |

*prof. Baldi will coordinate the course with the support of the professors of the experimental research Laboratories.

## GROUP 2 – ADVANCED COURSES

| Teacher | Course | Credits | Hours |
| --- | --- | --- | --- |
| A. Perreca | Advanced Interferometry | 3 | 24 |
| R. Menichetti e G. Marini (IIT) | Advanced statistical mechanics: Relaxation to equilibrium and transport phenomena | 3 | 24 |
| M. Dapor (ECT*) | Electron-Atom Collisions and Spin-Polarization Phenomena | 3 | 24 |
| M. Rizzi | Entanglement in Many-Body Systems: from Concepts to Algorithms | 3 | 24 |
| A. Chiasera (CNR- IFN) | Optical and Spectroscopic Diagnostic of Materials for Photonics | 3 | 24 |
| A. Quaranta, M. Lobino | Quantum Sensing | 3 | 24 |
| E. Scifoni (TIFPA-INFN) / D. Ascenzi | Radiation Chemistry | 3 | 24 |
| R. Battiston, L. Bruzzone, S. Vitale | Space-Based Observation Techniques and Methods | 6 | 48 |
| M. Rinaldi | Quantum field theory on curved space | 3 | 24 |
| I. Carusotto, A. Recati | Many-body physics with ultracold atoms and light | 3 | 24 |
| A. Legramandi, S. Singha Roy | Advanced topics in quantum information theory | 3 | 24 |

| | | | |
|---|---|---|---|
| S. Bandyopadhyay, R. Costa de Almeida | Quantum phases of matter: from Landau theory to topological order | 3 | 24 |
| A. Bartocci | Molecular modeling, design and graphics | 3 | 24 |
| G. Rastelli, A. Vinante | Engineered quantum nanosystems: theoretical methods and experiments | 3 | 24 |
| C. Gioia | Physical methods in polymer science | 3 | 24 |
| TALENT (Training in Advanced Low-Energy Nuclear Physics) | to be defined: http://www.ectstar.eu/talent | 6 | 45 |
| ECT* (European Centre for theoretical Studies in Nuclear Physics and related Areas) | ECT* Doctoral Training Programme 2023: Ab initio methods and emerging technologies for nuclear structure https://www.ectstar.eu/activities/trainings/ | 6 | |

**GRUPPO 3 - COMPETENZE TRASVERSALI/SOFT SKILLS**

| Docente | Corso | Crediti | Ore |
|---|---|---|---|
| Centro linguistico d'Ateneo | Academic Writing for the sciences and engineering | 3 | 24 |
| Centro linguistico d'Ateneo | Presentations for the sciences and engineering | 2 | 16 |
| Centro linguistico d'Ateneo | Academic writing II | 3 | 24 |
| Direzione Servizi Digitali e Bibliotecari | Use of electronic resources for bibliographic research | To be defined | To be defined |
| Direzione Servizi alla Ricerca e Valorizzazione | Training courses on specific aspects of the research work.<br>Details in the dedicated webpage: https://www.unitn.it/ricerca/109722/formazione-alla-ricerca | To be defined | To be defined |

# SCIENTIFIC WRITING, SPEAKING AND STORYTELLING

## Prerequisites

No particular prerequisite is required.

## Contents

The aim of this course is to offer fundamental tips and techniques for effectively writing and presenting scientific information. The skills developed during the classes will help improving effective scientific communication, both written and spoken, which can be applied to write the thesis, and to prepare other professional materials for presentations or publications.

The course objectives are:

1. Distinguish different types of research, their audiences and how research material might be effectively presented.
2. Understand the basis for preparing scientific and technical papers, and presentations.
3. Format documents and presentations to optimize their storytelling and visual appeal depending on the audience.
4. Accept constructive criticism and use reviewers' comments to improve quality and clarity of written reports and presentations.
5. Learn basic skills of nonverbal communication.

The course is structured in three modules: Module A focuses on writing skills; Module B focuses on the fundamental aspects of scientific storytelling and nonverbal communication in front of an audience; Module C is centered on the preparation of targeted presentations with visual aids (slides). Modules are 8 h long, and consist (indicatively) of 1 theoretical class (2 h), followed by 2 labs (3+3 h).

**Module A (Writing)**
The students will learn to identify the characteristics of good scientific writing, including academic style, coherence, and, word choice, and to avoid pitfalls and common mistakes. During the theoretical class (2 h), we will present different examples of writing approaches, and discuss pros and cons. We will then have two lab sessions, where students can bring a document they are working on, and use it as material to discuss and analyze with the rest of the group. If the number of attendees is too large, the students will be divided into subgroups.

**Module B (Storytelling and nonverbal communication)**
This module will look at how a narrative approach to scientific writing can improve the communication skills. In the first part we will explore the basic elements of a story (simplified hero's journey). Subsequently, by means of examples and basic exercises, we will write short pieces of narrative science communication, paying special attention to different audiences. In the final part of the module we will delve into the public presentation of the stories, looking at both the verbal as well as the non verbal delivery techniques and methods.

**Module C (Oral Presentations)**
We will address the basic rules for preparing and delivering a clear and successful oral presentation. In the theoretical class, we will identify how to structure a presentation based on the audience, and how to combine the slides material with the speech to make the message emerge. For the two labs classes, students will capitalize the lectures of modules B and C to prepare two 5 minutes presentations on the same topic of their choice, one designed for a non-scientific audience and one for a physics department. These presentations will provide a bases for group discussion.

## Schedule

Spring 2024 (dates will be decided based on the number of attendees)

## Exam

None.

## Bibliography

NA

UNIVERSITÀ DI TRENTO
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## ADVANCED TECHNIQUES IN EXPERIMENTAL PHYSICS, PROF. G. BALDI (COORDINATOR)

### Prerequisites

The knowledge of a physics graduate is requested.

### Contents

This course is organized as a collection of 4 lecture cycles on different topics in advanced experimental physics. Each cycle is given by an invited scientist or a member of the department, and consists in about 4-5 hours of lectures. The topics are selected every year in experimental research areas of interest of the physics department, giving priority to topics not already discussed in other dedicated PhD courses, as for instance:

1) Antimatter experiments, anti-hydrogen, positron beams, atomic physics experiments with positronium, positron and positronium for matter studies;
2) Applications of particle beams in medicine;
3) Biophysics, in particular methods for the conditioning/investigation of single biological molecules and for the imaging;
4) Cold gases condensates, atomic interferometry;
5) Instrumentation and methods for observational astrophysics and cosmology;
6) Instrumentation and methods in condensed matter and glasses and in surface science;
7) Instrumentation for synchrotron radiation and free electron laser based experiments;
8) Particle and radiation detectors;
9) Photonic devices;

The selection of topics of the course depends also on the availability of lecturers coming from other research institutes. The schedule of the course has to match the agenda of the lecturers and it is provisionally planned.

### Schedule

February – June 2024

### Exam

PhD students will give a seminar of 20 minutes on an experimental topic related to the four lectures or to an experimental research presented in the Dialogues, Colloquia and Joint Colloquia. The topic is freely chosen by the PhD student but must be previously agreed with the coordinators of the course and must be different from the field of research of the PhD student.

## MULTISCALE MODELING,
## PROF. F. PEDERIVA AND PROF. M. CALANDRA BUONAURA

### Prerequisites

Good knowledge of quantum and statistical mechanics as well as of manybody physics

### Contents

F. Pederiva (12 hours) on Basics of Quantum Monte Carlo: Variational Method and stochastic Imaginary Time Projection Method.

1) Construction of variational wavefunctions for the Monte Carlo solution of the Schroedinger equation
2) Optimization techniques
3) Variational MC with Neural States
4) Imaginary time projection and Diffusion MC
5) Importance sampling techniques in DMC
6) The Fermion Sign problem: workarounds and possible solutions

M. Calandra (12 hours) From the Schroedinger equations of ions and electrons to practical simulations schemes:

7) Exact Factorization
8) Ehrenfrest dynamics
9) Born-Oppenheimer dynamics
10) Classical Molecular Dynamics
11) The electron.phonon interaction.

### Schedule

To be defined

### Exam

Individually selected research problem, possibly leading to aninteresting research result/publication

### Bibliography

Giuliani and Vignale, Quantum Theory of the Electron Liquid, Cambridge University Press

Richard Martin, Electronic Structure Basic Theory and Practical Methods, Cambridge University Press

Dominik Marx and Jurg Hutter, Ab initio molecular dynamics: Theory and Implementation, available at https://www.theochem.rub.de/images/theochem/research/marx/marx.pdf

Grosso, Pastori, Pallavicini, Solid State Physics, Elsevier

Marvin L. Cohen and S. Louie, Fundamental of Condensed Matter Physics, Cambridge University Press

E. Lipparini, Modern May-Particle Physics (2nd edition), World Scientific

M. E. Tuckerman, Statistical mechanics: theory and molecular simulation, Oxford

## DATA ANALYSIS METHODS FOR PHYSICS, PROF. G.A. PRODI (COORDINATOR)

### Prerequisites

Basic knowledge of probability and statistics for the analysis of experimental data, basics on linear systems modeling and generic programming skills, at the level of a successful physics graduate.

### Contents

The course aims to deepen competences in experimental data analysis applications for physical sciences and foster their exploitation into the PhD thesis research. Content include an overview of frequentist and Bayesian statistics, selected applications to data analysis of time series and stochastic processes, applications of recent machine learning techniques. The course will include lecture cycles and hands-on sessions, given by the coordinator and other researchers.

### Schedule

Second Semester (April-June 2024)

### Exam

PhD students will give a seminar on an application of data analysis methods to an experimental research topic, possibly different from their main PhD thesis research, followed by an oral discussion.

### Bibliography

Particle Data Group: reviews on mathematical tools, https://pdg.lbl.gov/2022/reviews/contents_sports.html; textbooks

on **signal detection theory**

e.g. Elements of Signal Detection and Estimation
C. W. Helstrom, PTR Prentice Hall,
ISBN 0-13-808940-X

on **time-frequency signal processing**

e.g. A Wavelet Tour of Signal Processing
S. Mallat, Academic Press, Elsevier,
https://doi.org/10.1016/B978-0-12-374370-1.X0001-8

e.g. The Illustrated Wavelet Transform Handbook
P. S. Addison, IOP Publishing,
ISBN 0 7503 06920

on **Machine Learning**,

e.g. Machine Learning, T. M.Mitchell, McGraw-Hill Science/Engineering/Math; (March 1, 1997), ISBN: 0070428077;

Additional bibliography will be suggested during the course.

# ADVANCED INTERFEROMETRY, PROF. A. PERRECA

## Prerequisites

The knowledge of physics at graduate level is requested.

## Contents

The course will present advanced interferometric techniques for current and future experiments. Interferometry is an important investigative technique in the fields of astronomy, photonics, engineering metrology, optical metrology, plasma physics, biomolecular interactions, optometry and quantum mechanics. Several interferometers topologies are widely used in science for the measurement of small displacements, refractive index changes and surface irregularities down to quantum limited sensitivity. This course will describe principles and effects of various interferometry topologies and example of applications.

The course is organized as follows:

- Topology

Plane waves and Gaussian beams. Michelson Interferometer: contrast, displacement sensitivity, shot noise. Fabry-Perot cavities: stability, resonance condition, finesse. Other interferometer topologies: Sagnac interferometer, Mac-Zehnder interferometer: scheme and characteristics. More interferometric techniques: time delay interferometry, laser-ranging interferometry.

- Advanced Interferometry for Gravitational Waves detectors

Brief introduction to gravitational waves. Detection of gravitational waves. LIGO-Virgo interferometers at the time of their detections: Detection principle, Main noise contributions, Sensitivity curve. Future earth based GW detectors. Project for space based interferometers.

- Advanced techniques for interferometry

Brief introduction to electro and acoustic modulators. Pound-Drever-Hall technique for locking of the cavities. Modulation-demodulation techniques for interferometry locking. Radius of curvature measurement with interferometric technique.

- Simulations

Introduction to fINESSE software for optical simulations. Step-by-step examples of optical systems and their locking.

## Schedule

From November 2023 to February 2024

## Exam

Seminar and discussion

## Bibliography

Specific papers and books will be suggested during the lectures

## ADVANCED STATISTICAL MECHANICS: RELAXATION TO EQUILIBRIUM AND TRANSPORT PHENOMENA, PROF. R. MENICHETTI E G. MARINI

### Prerequisites

. Knowledge of analytical mechanics
. Knowledge of equilibrium statistical mechanics of classical and quantum systems

### Contents

. Hamiltonian flows
. Liouville equation
. Invariant measures
. Ergodicity and Mixing
. Bogolyubov-Born-Green-Kirkwood-Yvon (BBGKY) hierarchy
. Boltzmann equation and H-Theorem
. Boltzmann's most probable distribution method
. Weak perturbations: classical linear response theory
. Linear response theory for quantum systems
. Boltzmann equation and thermal transport

### Schedule

Second semester, 24 hours (12 lectures)

### Exam

Oral exam

### Bibliography

To be announced

UNIVERSITÀ DI TRENTO
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# ELECTRON-ATOM COLLISIONS ANS SPIN-POLARIZATION PHENOMENA, DR. M. DAPOR

## Prerequisites

Knowledge of modern physics

## Contents

Basic Principles
Pure States
Mixed States
Density Matrix
Mean Values of Operators
Unitary Operators, Qubits, and Entangled States
Polarized Electrons
Pure Spin States
Statistical Mixture of Spin States
Description of Electron Spin-Polarization by Density Matrices
The Dirac Equation and Spin
The Dirac Equation in a Central Field
The Dirac Radial Equations
Scattering Amplitudes
Lin, Sherman, and Percus Transformation
Phase Shifts and Differential Elastic Scattering Cross-Section
Sherman Function
The Role of Spin-Polarization in Elastic Scattering
Scattering Matrix for the Spin
Spin-Polarization Dependence of the Elastic Scattering Cross-Section
Spin-Polarization of an Electron Beam by Scattering
Change of Spin-Polarization after Scattering with Neutral Atoms of an Electron Beam Initially not Spin-Polarized
Change of Spin-Polarization after Scattering with Neutral Atoms of an Electron Beam Initially Spin-Polarized
Double Scattering Experiments

## Schedule

December 2023 - January 2024

## Exam

Oral examination

## Bibliography

J. Kessler, Polarized Electrons, Springer, Berlin Heidelberg 1985
M. Dapor, Electron-Atom Collisions: Quantum Relativistic Theory and Exercises, De Gruyter, Berlin/Boston 2022

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# ENTANGLEMENT IN MANY-BODY SYSTEMS: FROM CONCEPTS TO ALGORITHMS, DR. M. RIZZI (UNIVERSITÄT KÖLN)

## Prerequisites

Prerequisite for this course is a fair knowledge of the following topics:
- quantum mechanics (Hilbert spaces, probabilities, unitary evolutions, spin and Pauli matrices, composite systems, possibly density matrices)
- basic quantum many-body theory and statistical mechanics concepts (Fermionic/Bosonic statistics, 2nd quantization formalism, possibly some concept of renormalization and/or critical exponents)
- basic computer programming (language is not too important: e.g. Fortran, C++, Matlab, Mathematica)

The class will include a practical part consisting in writing up a simple Density Matrix Renormalization Group (DMRG) code based on Matrix Product States (MPS) formalism in order to solve some simple problems and to provide you a potential instrument for further studies in many fields.

## Contents

After a brief introduction of entanglement and other quantum information concepts (overlapping to other classes), leading to the Tensor Network Ansatz family, we will focus on their use as tools to investigate many-body systems and their quantum phases, both from the conceptual and from the computational point of view. The concepts and tools are so general that they can find application in different current research fields like, e.g., cold atoms in optical lattices, spins in magnetic materials, electrons in solids, quantum chemistry, topological materials, and so on.

The theoretical aspect will be complemented by a practical part, via the development of your own simple Density Matrix Renormalization Group (DMRG) code based on Matrix Product States (MPS) formalism in order to solve some simple problems (e.g. compute low energy spectra and/or structure factors of toy systems).

A tentative outline of the lectures is:

1. Intro: General motivation on Entanglement in Many-Body Systems
2. Intro: General idea behind Tensor Networks (TN), a menu thereof & three viewpoints on them
3. Rudiments of TN: graphical notation, area-law of entanglement, information-based renormalization, gauge freedom & canonical forms
4. Rudiments of TN: contractions & costs, extraction of observables & correlations, some exact examples
5. TN as numerical tool: description of usual goals (ground states / dynamics / thermal ensembles) & typical systems treated, Algorithm 1 – Time-Evolving Block Decimation (TEBD) for Matrix Product States (MPS)
6. TN as numerical tool: Algorithm 2 – Ground-State Variational Search, concept of Matrix Product Operator
7. TN as numerical tool: Algorithm 3 – Time-Dependent Variational Principle (TDVP) for longer-range models, Algorithm 4 – some rudiments of Thermal Ensembles
8. Advanced topic: Symmetry groups (quantum numbers) in TN algorithms, why and how (details on Abelian, hints to non-Abelian cases)
9. Advanced topic: Projected Entangled Pair States (PEPS) for 2D systems, generalities, algorithms & exact cases
10. Advanced topic / Outlook: a bird-eye view on all what we did not touch in detail (parent Hamiltonians, topological order, classification of phases, continuous MPS, holography, quantum chemistry, etc.)

This is not a too rigid scheme, and may be adapted on-the-fly to the skills and interests of the participants.

## Schedule

To be defined

## Exam

Free choice between the following options:

i) Little seminar on a selected topic of interest

ii) Short essay on a self-made numerical simulation
iii) Traditional oral exam

## Bibliography

1) do not feel scared by the articles, they are just as good as (or even more than) book chapters (and anyway we can help you through)
2) in case you are not able to download them (it should be possible from the Uni-Account), let us know and we will provide PDF's to you.

General literature on Quantum Information
- Quantum Computation and Quantum Information - Nielsen and Chuang - Cambridge Univ. Press
- Lecture Notes on Quantum Information - Preskill - www.theory.caltech.edu/people/preskill/ph229
- Computational Many-Particle Physics - edited by H Fehske, R Schneider, and A Weiße - Springer 2008 - http://link.springer.com/book/10.1007/978-3-540-74686-7/page/1
- special issue of Journal of Physics A, Vol 42, Num 50 - edited by Calabrese, Cardy, Doyon
- Amico, Fazio, Osterloh, Vedral - Rev. Mod. Phys. 80, 517 (2008) - arXiv:quant-ph/0703044
- Horodecki^4 - Rev. Mod. Phys. 81, 865 (2009) - arXiv:quant-ph/0702225
- Eisert, Cramer, Plenio - Rev. Mod. Phys. 82, 277 (2010) - arXiv:0808.3773

Specific literature on Tensor Networks
- Orus, Annals of Physics 349, 117-158 (2014) — arXiv:1306.2164v3
- Schollwöck - Ann. Phys. 326, 96 (2011) - arXiv:1008.3477

Deeper literature on Tensor Networks
- Schollwöck - Rev. Mod. Phys. 77, 259 (2005) - arXiv:cond-mat/0409292
- Cirac - lecture notes from Les Houches - arXiv:1205.3742
- Verstraete, Cirac, Murg - Adv. Phys. 57, 143 (2008) - arXiv:0907.2796
- Cirac, Verstraete - Jour. Phys. A 42, 504004 (2009) - arXiv:0910.1130
- Orus, Eur. Phys. J. B 87: 280 (2014) — arXiv:1407.6552v2

Own literature on Tensor Networks
- De Chiara, **MR**, Rossini, Montangero, J. Comput. Theor. Nanosci. 5, 1277_1288 (2008) (codesource www.dmrg.it),
- Silvi, Tschirsich, Gerster, Jünemann, Jaschke, **MR**, and Montangero, SciPost Phys. Lecture Notes 8 (2019)
- P. Schmoll, S. Singh, **MR**, R. Orús, arXiv:1809.08180

## Optical and Spectroscopic Diagnostic of Materials for Photonics, dr. A. Chiasera (CNR–IFN)

### Prerequisites

The typical skills of a Physics, Engineering graduate are requested.

### Contents

Phenomenological course

**Programme**

- Introduction to Glass Photonics
- From bulk to nano- and microscale photonics systems
- Rare earth –activated glasses
- Photonics devices fabrication and assessment
- Radiative and non-radiative transitions
- Transition probability
- Energy transfer
- Optical parameters, absorption and emission cross sections; Quantum efficiency
- Light scattering for characterization of material properties
- Confined structures: Planar waveguides, Nanospheres , Direct and inverse opals, Spherical Microresonators, 1D - Microcavities
- Transparent glass ceramics
- Resonant florescence line narrowing and spectral hole burning
- Homogeneous and inhomogeneous emission and absorption band
- Energy conversion
- Energy trapping
- Plasmonic structures
- Fluorescence enhancement using different sensitizers – metallic and semiconductor nanoparticles, lanthanides ions, nanocrystals
- Fibers and fiber lasers
- Nano -micro thermometers
- Solar energy conversion by quantum cutting
- Lightning
- Scintillators

### Schedule

From February to April 2024

### Exam

Seminar and discussion

### Bibliography

Specific papers and books will be suggested during the lectures.

## QUANTUM SENSING

### PROFF. A. QUARANTA, M. LOBINO

### Prerequisites

. Properties of electrical and magnetic fields.
. Optics.
. Electromagnetic waves.
. Principles of quantum mechanics.

### Contents

. Measurements and noise.
. Principles of photon detection.
. Single photon sources.
. Detection of entangled photons.
. Principles of quantum sensing.
. Advantages of quantum sensing.
. Examples and proof of principles of quantum sensing.

### Schedule

To be defined

### Exam

The exam will be a seminar about a topic selected by the student

### Bibliography

The bibliography is a collection of papers on the arguments discussed during the course. All the papers will be available during the course.

## RADIATION CHEMISTRY,
## DR. E. SCIFONI (INFN-TIFPA)

### Prerequisites

Elements of radiation physics and radiation-matter interaction. Basic knowledge of programming. Having followed the LM courses “Radiation: Detection and Applications” and “Medical Biophysics” is a useful complement.

### Contents

The course is intended to focus on the particular stage of radiation - matter interaction involving generation, transport and reaction of chemical species, mostly radicals and reactive oxygen species but including also electrons and ions, and is complementing the other courses on radiation biophysics held in the department.
Mostly dedicated to biomedical applications of radiation, it will cover also radiation effects on different materials, including an overview on chemical based dosimetry. The main scope is to provide the basis for spatiotemporal resolved, mechanistic investigations of different radiation-initiated processes.
It will last 21 h, covering the following topics:

Introduction: Stages of Radiation action in medium
Ionization and Excitation products
Electron Thermalization in media and Related Phenomena
Diffusion/Reaction dynamics
Free Radicals and Scavengers
Pulse radiolysis and related experimental techniques overview
Electron and Radical interactions with DNA
Chemical based Dosimetry
Simulation Codes for Homogeneous and Heterogeneous Radiation Chemistry
Some applications: FLASH radiotherapy
Hands-on exercises with TRAX-CHEM and TOPASnBIO
Outlook: Linking Radiation Biophysics to Molecular Dynamics

### Schedule

Second semester

### Exam

20 min seminar on a selected article OR Simulation exercise AND 10 min general questions

### Bibliography

Spotheim-Maurizot: Radiation Chemistry: From Basics to Applications in Material and Life Sciences
Von Sonntag: The Chemical Basis of Radiation Biology
Others to be provided

## SPACE-BASED OBSERVATION TECHNIQUES AND METHODS,
## PROFF. R. BATTISTON, L. BRUZZONE, R. DOLESI, W.J. WEBER

### Prerequisites

To be defined

### Contents

To be defined

### Schedule

To be defined

### Exam

To be defined.

### Bibliography

To be defined

## QUANTUM FIELD THEORY ON CURVED SPACE, PROF. M. RINALDI

### Prerequisites

Some knowledge of quantum field theory (free theory, e.g. the first part of the compulsory QFT I course for Unitn MSc students) and general relativity (for former Unitn students: MSc course on General Relativity and Cosmology or the last part of the BSc course on relativity) is recommended.

### Contents

Elements of free quantum relativistic fields in flat space. Acceleration effects in flat space: Unruh effect, moving mirrors. Particle creation in expanding universes. Renormalization of stress tensor. Hawking radiation. Analogue models of gravity: Hawking radiation in sonic black holes and particle creation in expanding ultracold gases.

### Schedule

March-May 2024

### Exam

Seminar on a topic of choice or on a research paper.

### Bibliography

"Quantum Fields in Curved Space", N.D. Birreli and P.C.W. Davies, DOI: 10.1017/CBO9780511622632
"Quantum Field Theory in Curved Spacetime : Quantized Field and Gravity", Leonard E. Parker and D. Toms, DOI: 10.1017/CBO9780511813924
Online material selected and provided by the lecturer.

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# MANY-BODY PHYSICS WITH ULTRACOLD ATOMS AND LIGHT, DR. I. CARUSOTTO – A. RECATI

## Prerequisites

Elementary quantum mechanics. Second quantization. Basics of statistical mechanics and of quantum statistical mechanics. Basics of wave and quantum optics.

## Contents

The first part of the course is devoted to atomic systems. We will start from a review of basic concepts on field theories and phase transitions. We will then describe the Gross-Pitaevskii and Bogoliubov theories for dilute Bose gases, and the diagrammatic theory of Fermi gases. Finally we will present an overview of one-dimensional strongly interacting systems, with a discussion of the available exact solutions and of the Luttinger liquid approach.

In the second part, we will move on to quantum fluids of light. We will give a comparative discussion of conservative vs. driven-dissipative dynamics and we will outline the different pumping schemes. We will present non-equilibrium generalizations of the non-equilibrium generalizations of the Gross-Pitaevskii equation and of the Bogoliubov theory and we will discuss analogies between the non-equilibrium Bose-Einstein condensation phase transition and the lasing threshold.

We will conclude the course with an interdisciplinary presentation of synthetic gauge fields and synthetic dimensions for atoms and photons, with their connections to synthetic magnetism and topological photonics.

## Schedule

24 hours. January-March 2024.

## Exam

Oral exam. Students can choose between I) a traditional exam with questions on the course and ii) a seminar on some topic of contemporary research, followed by a Q/A session. The specific subject of the seminar has to be agreed with the teacher.

## Bibliography

L. P. Pitaevskii and S. Stringari, *Bose Einstein condensation and superfluidity*. Oxford University Press, 2016.

G. Baym, C. Pethick, *Landau Fermi-Liquid Theory: Concepts and Applications.* WILEY-VCH Verlag GmbH & Co. KGaA, 1991.

I. Carusotto and C. Ciuti, *Quantum Fluids of Light*, Rev. Mod. Phys. **85**, 299 (2013).

J. Bloch, I. Carusotto, M. Wouters, *Non-equilibrium Bose–Einstein condensation in photonic systems*, Nature Reviews Physics **4**, 470 (2022).

T. Ozawa, H. M. Price, A. Amo, N. Goldman, M. Hafezi, L. Lu, M. Rechtsman, D. Schuster, J. Simon, O. Zilberberg, I. Carusotto, *Topological Photonics*, Rev. Mod. Phys. **91**, 015006 (2019).

Primary literature.

Lecture notes by the teacher, available at https://iacopo.carusotto.physics.unitn.it/teaching.html

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## ADVANCED TOPICS IN QUANTUM INFORMATION THEORY,
## DR. A. LEGRAMANDI- S. SINGHA ROY

### Prerequisites

Linear algebra, basics of quantum mechanics

### Contents

1. Introduction to classical information theory
   > Shannon entropy
   > Classical channels
2. Basics of quantum information theory
   > Density matrices
   > Quantum channels
   > Von Neumann entropy
   > Entropy inequalities
   > Mixed state entanglement
3. Entanglement as a resource for communication
4. Classification of quantum states: GHZ and W states
   >Characterization of the entanglement properties of multiqubit states
   > Monogamy of quantum correlations and its application
5. Entanglement witnesses
   >Basic definition, examples, usefulness, recent experimental realizations
6. More on quantum channels
   > Review on amplitude damping, phase damping, depolarizing channels and their Kraus's representation
   > Short review with examples on error correction codes
7. Hierarchy of quantum correlations: Quantum discord, Quantum entanglement, quantum steering, Bell inequality
   > Introduction about the type of quantum correlations, fundamental differences, their detection
8. Quantum information in many body systems
   > Short review on application of quantum entanglement in quantum many-body systems, Tensor networks
9. Replica trick for the entropy
   > Random states
   > Conformal field theories

### Schedule

Period: Tentatively, December (2023)- January (2024)

### Exam

Seminar and discussion

### Bibliography

1. M.A. Nielsen and I.L. Chuang, Quantum Computation and Quantum Information, Cambridge University Press (2001).
2. Edward Witten, "A Mini-Introduction To Information Theory", available at https://arxiv.org/abs/1805.11965
3. T.M. Cover and J.A. Thomas, "Elements of Information Theory", John Wiley & Sons (2006).
4. John Preskill's lecture notes on quantum information theory, available at http://theory.caltech.edu/~preskill/ph229/
5. Mark M. Wilde, Quantum Information Theory, Cambridge University Press (2017) .

UNIVERSITÀ DI TRENTO
Department of Physics
Doctoral Programme in Physics

## QUANTUM PHASES OF MATTER: FROM LANDAU THEORY TO TOPOLOGICAL ORDER, DR. S. BANDYOPADHYAY – R. COSTA DE ALMEIDA

### Prerequisites

Master level courses on Quantum mechanics and basic knowledge of programming

### Contents

**Background on phase transition**: Ising model, mean-field theory, critical exponent and universality classes, Brief on renormalisation and scaling.

**Phenomenological model for phase transitions**: Landau-Ginzburg theory, Order parameters, Particulars of statistical field and conformal field theories.

**Interacting quantum many-body systems**: Brief introduction to second-quantization and path-integral techniques for many-body bosons and fermions, Optical lattice systems with ultracold quantum gases.

**Quantum phases of the Bose–Hubbard model and its extensions**: Bose-Hubbard model, Single-site and advanced mean-field techniques to solve the model, Extensions multi-band and long-range interactions (dipolar and cavity mediated).

**Quantum simulation of quantum Hall effect**: Generation of artificial gauge fields for neutral atoms in optical lattices: Harper-Hofstadter model and regime for Quantum-Hall states.

**Numerical session I**: Exact diagonalization and mean-field techniques (site-wise + cluster) to solve the BHM model, Demonstration of strongly interacting and correlated phases.

**Laughlin states and Chern–Simons theory**: Introduction and basic concepts

**Topological aspects of lattice gauge theories**: Elitzur's theorem and derive topological partition function, Dijkgraaf–Witten model.

**Kitaev honeycomb model**: Derive Toric code as limit of Kitaev honeycomb model

**Ground state degeneracy, anyons**: GSD from TQFT's and anyons statistics, String-net models

**Topology in the Su–Schrieffer–Heeger model**: Band structure and topological properties of the SSH model

**Numerical session II**: Exact-diagonalization Kitaev's Honey-comb model/AKLT model with Tensor-Network techniques

### Schedule

Period: March 2024 and April 2024

### Exam

Evaluation based on programming projects (50% of the grade) and take home exercises/assignments (50% of the grade)

### Bibliography

1. Elements of phase transitions and critical phenomena by H. Nishimori and G. Ortiz
2. Quantum field theory and condensed matter by R. Shankar
3. Ultracold atoms in optical lattices by M. Lewenstein, A. Sanpera, V. Ahufinger
4. Quantum phase transitions by S. Sachdev
5. Quantum many-particle systems by J.W. Negele and H. Orland
6. Quantum field theory of Many-body systems by X.-G. Wen

## MOLECULAR MODELING, DESIGN AND GRAPHICS, DR. A. BARTOCCI

### Prerequisites

Molecular Dynamics simulations, Force-Field definition, Statistical Mechanics, Computational Chemistry and Biophysics basic concepts

### Contents

The course aims at giving initial concepts from quantum chemistry to classical force-fields for molecular dynamics. Main characters of the course will be the biological systems, as proteins, dna and lipids, with a more precise focus on protein—ligand systems. With this regard, particular attention will be devoted to ligand and small molecules parameterisation within all-atom and coarse—grained views. In order to give the students a better overview on such protein—ligand systems, characterizing analysis properties will be treated, discussed and analysed from a computed simulation (Hands on sessions), as well as scientific representations of the main system evolutions (Hands on scientific figures making and rendering). Finally, each participant will present one topic among those suggested by the lecturer: teamwork is possible and will be decided by the entire class.

INTRODUCTION TO QUANTUM CHEMISTRY: HF, BASIS SET DEFINITION, DFT AND EXCHANGE-CORRELATION FUNCTIONALS. INTRODUCTION TO QUANTUM MECHANICS-MOLECULAR MEHANICS (QM—MM)
PROTEINS, LIGANDS, DNA, ALL-ATOM (AA) CLASSICAL FORCE-FIELD (BONDED and NON-BONDED TERMS), MD SIMULATIONS PROPERTIES (FORCES, THERMOSTATS, BAROSTATS), GROMACS AND AMBER AS PRINCIPAL MD SIMULATIONS PACKAGES.
COARSE GRAINED (CG) MARTINI v.2/3 FORCE FIELD: MAPPING FROM ALL ATOM, BEAD TYPES, INTERACTIONS
LIGAND AND SMALL MOLECULES PARAMETERIZATIONS: AA AND CG FORCE FIELDS
PROTEIN—LIGAND SYSTEMS: BINDING SITE SEARCH (DIFFUSION AND KINETICS), BOUND STATE SIMULATIONS AND ANALYSIS (RMSD, SOLVENT ACCESSIBLE SURFACE AREA SASA, CLUSTER ANALYSIS, BINDING AFFINITIES, PROTEIN—LIGAND CONTACTS, RADIAL DISTRIBUTION FUNCTIONS), ENHANCED SAMPLING TECHNIQUES (REPLICA EXCHANGE, METADYNAMICS)
HANDS ON SESSION: ANALYSIS OF PROTEIN—LIGAND (AA AND CG) MD SIMULATIONS ON GROMACS, SYSTEM SETUP ON AMBER
HANDS ON SCIENTIFIC FIGURES MAKING AND RENDERING: VMD
HANDS ON SCIENTIFIC FIGURES MAKING AND RENDERING: PYMOL
TOPIC DISCUSSION
TOPIC DISCUSSION

### Schedule

Second semester: one meeting per week — 8 meetings in total of 2.5hrs + 2 meetings of 2hrs- 24 hrs (3CFU)

### Exam

The evaluation will be done through “Hands on session” exercise on a protein—ligand system and on a chosen presentation (Topic discussion).

### Bibliography

Reading material will be provided in every lecture, based on recent and milestone literature.

## ENGINEERED QUANTUM NANOSYSTEMS: THEORETICAL METHODS AND EXPERIMENTS, DR. G. RASTELLI – A. VINANTE

### Prerequisites

Knowledge of quantum and statistical mechanics

### Contents

THEORY

Theory of open quantum systems. Caldeira-Leggett model. Quantum Langevin equations. Quantum noise. Input-output theory. Decoherence. Basics of superconductivity. Josephson effect. Optomechanical systems. Nanomechanical systems. Superconducting Josephson circuits. Superconducting qubits.

EXPERIMENTAL METHODS

Mechanical systems with small dissipation. Cooling techniques. Levitated mechanical systems. Applications in fundamental physics. Superconducting microwave circuits and technologies. Microfabrication of thin film devices. SQUIDs. Parametric amplifiers. Kinetic inductance devices. Qubits and circuit-QED.

### Schedule

March-May 2024

### Exam

Free choice between the following options:

- Seminar of 20 minutes on a topic of the course;
- Individual selected research problem agreed with the coordinators of the course;

### Bibliography

1) A. Zagoskin: Quantum Engineering: Theory and Design of Quantum Coherent Structures
2) C. Gardiner, P. Zoller: The Quantum World of Ultra-Cold Atoms and Light - Book I: Foundations of Quantum Optics
3) A. Blais et al: Circuit Quantum Electrodynamics, Rev. Mod. Phys. 93, 25005 (2021)

# PHYSICAL METHODS IN POLYMER SCIENCE

DR. C. GIOIA

## Prerequisites

For a fruitful exploitation of the content of this course, the students should have an established understanding of general, and organic chemistry.

## Contents

- Polymeric materials: definition and classification.
- Introduction on the thermo-mechanical properties of polymers.
- Methods for the determination of the molecular weight.
- Thermal properties and methods of characterization.
- Mechanical properties of the polymers and methods of characterization.

## Schedule

2nd semester

## Exam

The evaluation will be discussed with the students at the beginning of the course.

## Bibliography

- Suitable slides will be provided.
- For additional information:
    - “Essential of polymer science and engineering”, P. C. Painter, M. M. Coleman