MANY BODIES PHYSICS

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Moduli	Settore/i	Tipo	Ore	Docente/i
FISICA DEI SISTEMI A MOLTICORPI	FIS/03	LEZIONI	54	MARIA LUISA CHIOFALO

Learning outcomes

Knowledge

1. Develop conceptual, procedural, and factual knowledge in the physics of many interacting quantum particles, where after acting via temperature, dimensionality, interaction strength, extreme quantum behavior and correlation effects can be realized in charge/density and spin properties.
The course is aimed to:
(a) qualitatively discuss via basic physics of emergent ideas from experimental and everyday-life facts, while - whenever possible - deepening on the use of experimental methods;
(b) formalize the concepts (**conceptual knowledge)** and
(c) develop and classify the knowledge of theoretical methods (with an eye also to simulational methods) needed to perform quantitative predictions (**procedural and factual knowledge**), including Theory of linear response and correlation functions, Quantum fluido- and hydro-dynamics, (Time-Dependent) Density Functional Theory, Green's functions and perturbative expansions, Bosonization techniques for 1D systems.

Assessment criteria of knowledge

Assessment is performed via **oral exam**. The exam stems from a problem in many-body physics not discussed during the course, that the student may choose (in autonomy or accompanied by the teacher). Assessment is performed according to the following competences Areas:
(a) understanding ideas and concepts, and competence in communicating them after using basic-physics knowledge;
(b) competence in formalizing the concepts and treating them via one or more among the methods developed during the course with related procedures;
(c) competence in relating the conceptual comprehension and the problem formalization with the phenomenological and experimental available facts, and having hints about possible applications;
(d) autonomy, awareness of conceptual maps, learning process and contents, effectiveness in scientific communication.

The following composition is used
– up **18 points** for Area **(a)**
– up **6 points** for Area **(b)**
– up **4 points** for Area **(c)**
– up **5 points** for cross and life-skills **(d)**

Skills

1. Organizing the present disciplinary knowledge in the same conceptual mapalong with thermodinamics, statistical mechanics, phase transitions, qantum mechanics, quantum field theories, condensed matter in its diverse realizations, making clear the emergence of how macroscopic properties are governed by conservation laws and spontaneous symmetry breakings accompanied by the appearence of elasticity, low-frequency dynamical modes, and defects.
2. Selecting the most convenient procedure for the solution of a given problem
3. Application of calculus techniques related to different solution procedures

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Behaviors

- Curiosity
- Committment
- Active involvement
- Creative approach
- Group working
- Faireness during evaulation

Assessment criteria of behaviors
During the lecturing time, via interactions with students.

Prerequisites
Prerequisite is the basic knowledge of classical dynamics, thermodynamics and elements of statistical mechanics, electromagnetism, structure of matter, quantum physics.
Very useful and preferable, though not compulsory, is the knowledge of solid-state physics

Teaching methods
Two case studies are illustrated, complementary with respect to charge/density and spin charecteristics, and extracted from frontier research fields. In particular, quantum fluids in reduced, dimensionality and ultracold quantum gases. Case studies are used to acquire the following competences:
(a) qualitatively discuss via basic physics of emergent ideas from experimental and everyday-life facts, while - whenever possible - deepening on the use of experimental methods;
(b) formalize the concepts (**conceptual knowledge);**
(c) develop and classify the knowledge of theoretical methods (with an eye also to simulational methods) needed to perform quantitative predictions (**procedural and factual knowledge**);
(c) relate the conceptual comprehension and the problem formalization with the phenomenological and experimental available facts, and having hints about possible applications;
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Syllabus
A. Introduction and conceptual map of the essential ideas...
...qualitatively discussed via examples anticipated from the course itself

B. Structure and scattering
Generalities and essential concepts. Measurements and Correlation functions, Response functions, Quantum Hydrodynamics via a simple model.

C. Theoretical Methods for strongly correlated many-body systems
C.1 Systems with maximal symmetry. Development of theoretical methods, starting from the measurement of correlation functions which have been phenomenologically introduced in B. Discussion of the relationships among the different methods, enlightening goods and bads.

- Formal development of the Theory of Linear Response: Definitions and properties- Fluctuation Dissipation Thorem - Sum rules - Applications: calculation of response function within the Random-Phase Approximation (fermions and bosons) - Concept od local field factor and self.-consistent theories beyond mean-field
- Quantum Hydrodynamics: Microscopic derivation of the equations starting from conservation laws - Transport coefficients as special limits of response functions and Kubo relations- Static susceptibilities as theoremodynamic derivatives of conserved quantities. Relationship with Linear Response. Relationship with experiments: landau-Placzek ratio and examples.
- (Time-Dependent) Density Functional Theory: Definitions - Theorem of Hohenberg and Kohn - Kohn and Sham scheme - Local Density Approximation - Exchange and correlation potentials and relationship with lineas response theory - Current functional and TDDFT, Funzionale di corrente e TDDFT, relationship with Linear Response and microscopic formulation of Navier-Stokes equations as related to quantum hydrodynamics.
- Correlation functions and Green's functions (zero and finite temperature): Definitions and properties - Boundary conditions - Equations of motion as a technique to derive consistent approximations - Non-equilibrium Green's functions - A dictionary with response functions - Generating functionals - Wick's theorem - Finite temperature and the contour-integral method - Perturbative

techniques and Feynman diagrams - Examples including phonon and fermion systems to low-order - Landau Theory of Fermi Liquids
- **Introduction to Path Integrals [If time allows it]**
- Relationship between the theoretical methods learned and experimental methods, with examples from different spectroscopies (matter, spin, and optical probes) and transport measurements

C.2 Systems with broken symmetry

- Concept of order parameter
- Landau and Landau-Ginzburg theory for uniform (Ising model) and non-uniform order parameter – Complex order parameter and neutral/charged superfluid - Critical exponents
- Dynamical effects: Anderson-Higgs mechanism and Goldstone modes - Analogy between superconductivity and electroweak theory
- Introduction to the concepts of scaling, critical and universality – Physical meaning of the Renormalization Gropuo Theory-Map of order parameters by broken symmetry -
- Conditions of validity for mean-field theories and thermal and quantum (as e.g. due to correlations and reduced dimensionality) fluctuations

C.3 Effects of reduced dimensionality: the 1D case

- Specialty of 1D systems: always strongly correlated and collectivization of excitations
- Bosonization techniques
- Luttinger Liquids: structure and theremodynamic properties

D. Applications of the methods via two case studies:
D.1 Case stuudy: *superfluidity and Bose-Einstein Condensation of neutral and charged Fermi and Bose systems.* Applying: Theory of linear response to the microscopic calculation of the superfluid density/moment of inertia and the relationship between superfluid and condensate fraction - DFT and TD extension - Hydrodynamics and microscopic two-fluid equations - Green's functions treatment (peculiarities: Ward identities and conseving vs. gapless approximations).
D.2 Case study: *Typical phase diagrams in 1D systems with Charge/density and Spin-Density Waves.* 1D systems and bosonization techniques.

<u>In addition, the following parts can be discussed after specific agreement and planning:</u>

E. Principles for Simulational methods for strongly correlated systems
[Via ad hoc seminars within collaborations with other courses and teachers]
E.1 Quantum Monte Carlo (QMC): Variational, Diffusion, Reptation, Path-Integral QMC.
E.2 Implementations of DFT.
E.3 Density Matrix Renormalization Group (DMRG).
E.4 Theoretical laboratories.

F. Defects: a dictionary [if time allows it]
Carachterization according to broken-symmetry properties. Generalities on topological defects, examples and applications: vortices and dislocations, Kosterlitz-Thouless transition. Generalities on domains, walls, and solitons, examples and applications.

Bibliography

Textbooks and articles are available at the Physics Library and/or online. Additional material is on the elearning website of the course, where a guided tour of the different textbooks and papers is provided.

5.1 General:

– Piers Coleman, *Introduction to Many-Body Physics,* Cambridge University Press (2015)

– L.P. Kadanoff and G. Baym, *Quantum Statistical Mechanics,* Benjamin (1962)

– P.M. Chaikin and T.C. Lubensky, *Principles of Condensed Matter Physics*, Cambridge University Press (1995)

– G. Iadonisi, G. Cantele, and M.L. Chiofalo, *Introduction to Solid State Physics and Crystalline Nanostructures*, Springer (2014)

– G. Grosso and G. Pastori Parravicini, *Solid State Physics*, Academic Press (2000)

5.2 For specific parts of the course:

– P.C. Martin, *Measurements and Correlation Functions*, Gordon and Breach (1968)

– G. Vignale, C. A Ullrich, S. Conti, *Time-Dependent Density Functional Theory and beyond the Adiabatic Local Density Approximation*, Phys. Rev. Lett. 79, 4878 (1997)

– Baym, *Microscopic Description of* Superfluidity, Math. Methods in *Solid-State&Superfluid Theory*, Clark&Derrick Eds., Oliver&Boyd (1969)

– P.C. Hohenberg and P.C. Martin, *Microscopic Theory of Superfluid Helium*, Annals of Physics 34, 291-359 (1965)

– Giamarchi, *Quantum Physics in One Dimension*, Oxford Science Pub. (2006)

– W.M. Foulkes, L. Mitas, R.J. Needs, and G. Rajagopal, Quantum Monte Carlo Simulations of Solids, Revue of Modern Physics 73, 33 (2001)

– U. Schollwok and S.R. White, *Methods for Time Dependence in DMRG*, in *Effective Models for Low-Dimensional Strongly Correlated Systems*, G.G. Batrouni and D. Poilblanc Eds., p. 155 AIP, Melville, New York (2006)

Additional suggested reading:

– P. Nozières and D. Pines, *Theory of Quantum Liquids I – II*, Westview Press (1999); Pines, *The Many-Body Problem*, Wiley (1997)

– D. Forster, *Hydrodynamic Fluctuations, Broken Symmetry, And Correlation Functions,* Adv. Books Classics (1995)

– L. A. Bloomfield, *How Things Work*, Wiley (2013)

Non-attending students info

Follow the material organized on the elarning page of the course

Assessment methods

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Notes

The course is aimed to students who wishes to specialize their career in condensed matter physics and theoretical physics, AND to students who simply wish to complement their knowledge with respect to other specific fields. A specific choice of the course is to privilege a wider conceptual and methodological vision more than technical details, which can be deepened at any given and useful time.

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