Course on "Statistical Physics of Fields In and Out of Equilibrium"

School of Physics, Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
Spring Semester 2016 (1394-1395) / Code (IPM): 113558

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- **Time:**
  Sundays, 14:00 - 15:40 and 16:30 - 18:10 (four-unit course)
  Starting from Sunday February 14, 2016 (Bahman 25, 1394)

- **Place:**
  Classroom A, Ground floor, Farmanieh Central Building
  Institute for Research in Fundamental Sciences (IPM), Farmanieh Campus,
  No. 70, Lavasani St., Tehran, Iran

- **Website: http://physics.ipm.ac.ir/~naji/fields_SS2016.html**

- **Tutorial sessions:**
  Wednesdays, 10:30 - 12:30, Classroom A, by Dr. Bahman Roostaei (IPM)

- **Final grade:**
  The final grade will be determined based on a number of factors including **homework assignments**, active contribution to **tutorial sessions** and a **term essay**. The students may opt for taking a **final exam** instead of doing a term essay (see below for further details).

- **Intended audience and pre-requisites:**
  This course is intended primarily for Ph.D. students in Physics. It may nevertheless be useful for and attended by Ph.D. students in closely related fields and advanced M.Sc/B.Sc. students with an elementary knowledge of **thermodynamics** & **statistical mechanics** (comparable to the level of standard B.Sc./M.Sc. textbooks in Physics). All students who sign up for the course will be expected to attend the lectures and tutorial sessions on a regular basis and do the homework assignments. Auditing students will be required, as a form of contribution to the class, to give a **short seminar** during or at the end of the course on a subject they select from a list of suggested topics.

- **Scope & summary:**
  Starting with a short review of the basics of statistical mechanics and thermodynamics, I shall give an overview of statistical fields in and out of (thermal) equilibrium with emphasis made (by giving various examples) on their applications in soft matter and condensed matter physics. This will be followed by discussing methods of constructing field theories either phenomenologically or systematically based on microscopic Hamiltonians; in the latter case, I shall discuss in detail a modern (re)formulation of the exact Hubbard-Stratonovich transformation. The essential methodology of statistical field theory shall be covered in several lectures throughout the course, ranging from elements of the calculus of variations, functional integrals (and path integrals), perturbative expansions and Feynman diagrams to real-space and momentum-space (Wilson's) renormalization group techniques. Other useful notions such as continuous symmetries, Noether's theorem, Schwinger-Dyson equations, Ward identities, zero

modes and Goldstone's theorem as well as some less familiar methods in calculating functional determinants (e.g., Pauli-Van Vleck-Morette determinant, Gel'fand-Yaglom formalism & Zeta-function regularization) will be discussed in detail and their utility is demonstrated in the context of **Coulomb fluids (or "Coulomb gases")**, **fluctuation-induced phenomena (Casimir & pseudo-Casimir effects)** and **equilibrium critical phenomena and phase transitions**. While ample time will be given to these latter topics in the first part of the course on **statistical physics of fields in equilibrium**, I shall also devote some time to discuss a few subjects on **statistical physics of fields out of equilibrium** in the second part of the course. Starting with a short review of dissipative dynamics of particles, I shall discuss the dissipative dynamics of critical fields near equilibrium and, if time permits, far from equilibrium in the example of Kardar-Parisi-Zhang equation, followed by preliminaries of the Martin-Siggia-Rose functional-integral approach to field dynamics. The lectures in each of the main areas covered in the course will be supplemented by slide-presentation sessions, illustrating real-world examples, key experimental and computational evidence as well as modern applications and recent advances made in the study of the topics in question. The homework assignments shall be designed in such a way as to complement the subjects discussed in the lectures. **A more comprehensive and updated list of subjects covered in this course is available at the course website.**

◉ **Homework, term essay & final exam:**

Homework assignments will be given on a regular basis and in the form of problem sets that can be dowloaded from the course website. The homework solutions must be typed in English using LaTeX. The source tex/figure files and a pdf output, carefully proof-read for any typos and/or grammatical errors, must be submitted via email. The **homework solutions** will be graded, making altogether 40% of the final score with the rest coming from a **term essay** (40%) and an evaluation by the tutor of the active participation and contribution of the students to the discussions in the **tutorial sessions** (20%). The students who sign up for the course will be required to **write** and **present** a term essay on a subject they select from a list of suggested term-essay topics; the list along with further instructions will be made available on the course website in due course. Students can propose other topics for their term essay and they need to confirm their choice of the term-essay subject with me beforehand. Term essays must be prepared in the form of standard scientific reports or review articles using a LaTeX template and other specifications to be circulated with the list of topics. The source tex/figure files and a pdf output of the term essay must be submitted via email before a deadline that will be announced later. The students may opt for taking a **final exam instead of doing a term essay** but they need to inform me of their decision **two weeks before the essays due date**. Auditing students will be required, as a form of contribution to the class, to give a **short seminar** during or at the end of the course on a subject they select from the list of suggested term-essay topics.

◉ **References:**

There are many valuable books covering the topics of this course at different levels. I will not follow any particular textbook in general and rely mostly on self-designed lectures, especially for my lectures on **field theory for Coulomb fluids**, **fluctuation-induced phenomena (Casimir & pseudo-Casimir effects)** and **statistical physics of fields out of equilibrium**, for which there are fewer textbooks or other references that can be suitable for this course. For the lectures on **methods of statistical field theory** and **equilibrium phase transitions and critical phenomena**, the students can use any of the references listed below; I can specifically recommend Kardar (2007), Goldenfeld (1992), Brezin (2010), Altland & Simons (2010) and Kleinert (1989).

LIST OF REFERENCES BY TOPIC

- **Statistical field theory, phase transitions & critical phenomena:**

Key textbooks for this part of the course:

✤ M. Kardar, *Statistical Physics of Fields* (2007)
✤ N. Goldenfeld, *Lectures on Phase Transitions and the Renormalization Group* (1992)
✤ E. Brezin, *Introduction to Statistical Field Theory* (2010)
✤ A. Altland & B. Simons, *Condensed Matter Field Theory* (2010)
✤ H. Kleinert, *Gauge Fields in Condensed Matter: Vol. 1* (1989)

Other excellent references & textbooks: (in reverse chronological order)

- H. Nishimori & G. Ortiz, *Elements of Phase Transitions & Critical Phenomena* (2010)
- G. Mussardo, *Statistical Field Theory* (2010)
- D.I. Uzunov, *Introduction to the Theory of Critical Phenomena* (2010)
- J. Zinn-Justin, *Phase Transitions and the Renormalization Group* (2007)
- W.D. McComb, *Renormalization Methods: A Guide for Beginners* (2004)
- J. Zinn-Justin, *Quantum Field Theory and Critical Phenomena* (2002)
- H. Kleinert & Schulte-Frohlinde, *Critical Properties of ϕ^4-Theories* (2001)
- P.M. Chaikin & T.C. Lubensky, *Principles of Condensed Matter Physics* (1995)
- J.J. Binney et al., *The Theory of Critical Phenomena* (1992)
- J. Yeomans, *Statistical Mechanics of Phase Transitions* (1992)
- C. Itzykson & J.-M. Drouffe, *Statistical Field Theory: Vols. 1* & 2 (1989)
- G. Parisi, *Statistical Field Theory* (1988)
- K. Huang, *Statistical Mechanics; 2nd edition* (1987), Part C
- S.-K. Ma, *Modern Theory of Critical Phenomena* (1976)
- F. Ravndal, *Scaling and Renormalization Groups* (1976)
- H.E. Stanley, *Introduction to Phase Transitions & Critical Phenomena* (1971)

- **Statistical physics of fields out of equilibrium:**

✤ **Self-designed lectures**; other useful references (of varying levels of difficulty):

- U.C. Täuber , *Critical Dynamics* (2014)
- A. Kamenev, *Field Theory of Non-Equilibrium Systems* (2011), Ch. 8
- M. Kardar, *Statistical Physics of Fields* (2007), Ch. 9
- G.F. Mazenko, *Nonequilibrium Statistical Mechanics* (2006), Ch. 8
- P.M. Chaikin & T.C. Lubensky, *Principles of Condensed Matter Physics* (1995), Ch. 8
- N. Goldenfeld, *Lectures on Phase Transitions & the Renormalization Group* (1992), Ch. 8
- S.-K. Ma, *Modern Theory of Critical Phenomena* (1976), Ch. XI- Ch. XIV
- D. Forster, *Hydrodynamic Fluctuations, Broken Symmetry & Correlation Functions* (1975)

- **Field theory for Coulomb fluids (or "Coulomb gases"):**

✤ **Self-designed lectures**; a few book chapters and review papers will also be introduced as possible additional references during the course.

- **Fluctuation-induced phenomena (Casimir effect):**

✤ **Self-designed lectures**; the following books may also be consulted by the students:

- P.W. Milonni, *The Quantum Vacuum* (1994)
- V.A. Parsegian, *Van der Waals Forces* (2005)
- M. Bordag et al., *Advances in the Casimir Effect* (2009)