Syllabus
Thermodynamics and Statistical Mechanics
(Physics 8150)
Spring Semester 2018

Instructor

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Office Hours

MWF 1:30 – 2:30 or directly after class; I have an open door policy: simply come on an as needed basis any time. **Students are strongly encouraged to make use of the office hours, to discuss homework assignments and for conceptual questions.**

Prerequisite

Undergraduate Thermodynamics (Physics 4650 or similar).

Class Hours

MWF 10:10 – 11:00, 116 Kinard (lecture). If I am late for class and do not have a substitute, I do not expect students to wait more than 15 minutes.

Thu 5:30 pm (after the colloquium), 116 Kinard (recitation).
The recitation session is not graded. We will discuss and solve problems related to the week's material covered in the lectures. Attendance is not mandatory but strongly encouraged. Students are encouraged to request the discussion of specific problems they are interested in, given that the instructor is made aware of this request the business day before the recitation class.

Attendance Policy

Attendance is required for the first class. Thereafter, it is not required but is *strongly recommended*. It is the responsibility of the student to be aware of what is announced in class, including changes to homework assignments. Please also see the general statement on attendance in the Graduate Announcements.

Required Texts

Statistical Mechanics (Third Edition) by Pathria & Beale; Elsevier, ISBN 978-0-12-382188-1, 718 pages, 2011; List Price US$ 94.95; it is important that you have the 3rd edition. **The major part of the lecture will follow this book!** For errata see: http://www.elsevierdirect.com/v2/companion.jsp?ISBN=9780123821881

Thermodynamics and Statistical Mechanics by Greiner, Neise, Stöcker; Springer, ISBN 0-387-94299-8, 463 pages, 1994; List Price US$ 79.20. **The first part of the course (review of thermodynamics) will follow this book before switching to Pathria &**

Beale. It also provides a comprehensive summary of statistical mechanics although on a somewhat lower level than Pathria & Beale.

Recommended Texts

Statistical Mechanics by R. Kubo; North Holland Personal Library (now Elsevier), ISBN 0-444-87103-9, 425 pages, 2004; Lots of problems with solutions: excellent for practicing; not suitable as stand-alone textbook.

Other commonly used texts are: *Statistical Mechanics and Thermal Physics* by Reif; *Statistical Mechanics in a Nutshell* by Peliti; and *Statistical Physics* by Landau and Lifshitz

Class Web Page

The course web site can be accessed via Canvas. Course announcements, assignments, instructional material etc. can be found there.

Course Objectives

The overall objective is to provide the student with an advanced graduate level foundation for any research involving statistical mechanics. This includes the theoretical basis, including quantum statistics, for more advanced topics such as criticality, complex magnetic systems, Brownian motion, etc.

Course Outline

1. <u>Review of thermodynamics (about 3 weeks):</u> introduction, macroscopic vs. microscopic variables, extensive and intensive thermodynamic variables, densities and fields, kinetic theory of the ideal gas, first and second laws of thermodynamics, reversible and irreversible cycles, entropy, thermodynamic assemblies and potentials, stability, Legendre transformations between assemblies, Maxwell relations, coexistence, Clausius-Clapyron equation, van der Waals equation of state, Maxwell construction.
2. <u>Statistics (about 1 week):</u> random variables, averages and variances, binomial distribution, continuous distributions, normal distribution, central limit theorem, pseudo-random numbers.
3. <u>Foundations of statistical mechanics with applications (remainder of the semester):</u>
    i. Statistical basis of thermodynamics, classical ideal gas, correct enumeration of microstates,…
    ii. Microcanonical ensemble, phase space, Liouville's theorem,…
    iii. Canonical ensemble, partition function, equipartition and virial theorems, paramagnetic systems, harmonic oscillators in heat bath,…
    iv. Grand canonical ensemble, fluctuations, phase equilibrium,…
    v. Essentials of quantum statistics, indistinguishable particles, density matrix,…
    vi. Theory of simple gases in a quantum mechanical ensemble context, internal motions,…
    vii. Ideal Bose systems, ultra-relativistic case, Bose-Einstein condensation, blackbody radiation, liquid helium,…

viii. Ideal Fermi systems, ultra-relativistic case, magnetic behavior, electron gas, statistical model of the atom,…
ix. Thermodynamics of the early universe

Learning Outcomes

1. Essentials of equilibrium thermodynamics
   a. Be able to apply the 0^{th} and 1^{st} laws of thermodynamics and the concept of cyclic processes to derive the 2^{nd} law and recognize (i) the resulting equilibrium condition for entropy and (ii) the importance of the fundamental relation in terms of system knowledge. This includes the concepts of reversible and irreversible processes and the 3^{rd} law.
   b. Recognize that intensive properties are derivatives of the fundamental relation with respect to the corresponding extensive quantities and apply the concept to derive the entropy of the ideal gas.
   c. Be able to identify the appropriate thermodynamic potential for a given system/process and compute intensive and extensive variables from that. This includes the computation of specific heats, the derivation of equations of state and the proper use of the Maxwell relations for thermodynamic calculations.
   d. Be able to identify the equilibrium conditions for 1^{st} and 2^{nd} order phase transitions and apply the concept to find the pressure dependence of the transition temperature and to solve standard problems such as osmotic pressure, chemical reaction rates, latent heat, etc.
2. Review of basic statistics/combinatorics
   a. Be able to compute the number of permutations for various subsets of distinguishable and indistinguishable particles.
   b. Be able to derive the binomial distribution, recognize its large number approximation as the normal distribution using the Sterling approximation, and appreciate the central limit theorem to an extent that allows him/her to apply the concept to a given problem. Be able to derive the Poisson distribution.
   c. Be able to compute the mean and standard deviation of a given variable if the probability distribution is known, for both the discrete and continuous cases.
3. Elements of ensemble theory
   a. Recognize the concept of microstates and the resulting fundamentally important connection between thermodynamics (entropy) and statistical mechanics (microstates).
   b. Be able to compute the number of microstates for simple systems using combinatorics and derive thermodynamics properties for these systems.
   c. Be able to explain the reason for the Gibbs correction factor in the Sackur-Tetrode equation and generally recognize the former's importance for distinguishable and indistinguishable particles. The student should be able to apply the Sackur-Tetrode equation to compute thermodynamics properties of the ideal gas including mixing entropy.
   d. Recognize phase-space as the appropriate framework for ensemble theory and be able to compute the number of microstates and the density of states for standard microcanonical ensembles using phase-space considerations. Examples include

1D, 2D, 3D classical ideal and ultrarelativistic gases, classical and quantum mechanical rotator, and the harmonic oscillator.

   e. Recognize the connection between microcanonical and canonical ensemble theory, be able to identify free energy as the appropriate thermodynamic potential, and be able to compute the partition function for standard systems of distinguishable and indistinguishable particles (such as the ideal gas, the harmonic oscillator, paramagnet, etc.) and derive thermodynamic properties from that.
   f. The student should recognize the connection between canonical and grandcanonical ensemble theory and apply the latter to standard systems such as the ideal gas, the harmonic oscillator. Furthermore, the student should be able to apply the concept to give an explanation for critical points, and in general to solve standard phase transition problems such as gas adsorption on surfaces.
   g. Be able to identify the appropriate ensemble for a given system and derive thermodynamic properties from that.

4. <u>Basics of quantum statistics and theory of simple gases</u>
   a. Be able to apply the concept of density matrix to simple quantum systems for mixed and pure state situations. Be able to compute and evaluate the density matrix for standard systems in microcanonical, canonical and grandcanonical settings.
   b. Be able to interpret the partition function for product states, anti-symmetric wave functions and symmetric wave functions in terms of Maxwell-Boltzmann, Fermi-Dirac and Bose-Einstein statistics and compute mean occupation numbers and energies in degenerated and non-degenerated settings for standard problems.
   c. Be able to apply MB statistics to gases with internal degrees of freedom and compute resulting contributions to entropy, specific heat, etc.
5. <u>Ideal Bose systems</u>
   a. The student should recognize the concept leading to Bose-Einstein condensation and apply this to 2D and 1D cases (test for BE condensation, for example).
   b. Recognize the differences in the thermodynamic behavior (for example: specific heat) between BE and MB statistics and be able to apply this to explain the anomalous behavior of the specific heat of 4He (critical temperature).
   c. Be able to compute blackbody radiation in 1D, 2D, 3D cases from BE considerations of the ultrarelativistic Bose gas.
6. <u>Ideal Fermi systems</u>
   a. Recognize the difference between Fermi and Bose systems, and be able to compute the Fermi energy and occupation numbers for simple 1D, 2D, 3D Fermi systems in the low temperature limit.
   b. Be able to compute specific heat and other thermodynamic properties of simple Fermi systems and be able to explain why electrons in a metal do not contribute to the specific heat.
   c. Be able to apply the FD statistics to simple electric and magnetic systems such as thermionic emissions and Pauli paramagnetism.

Disclaimer: "Students may vary in their competency levels on these abilities. They can expect to acquire these abilities only if they honor all course policies, attend class regularly, complete all assigned work in good faith and on time, and meet all other course expectations of them as a student."

Homework

Written homework is very important to practice the theoretical concepts discussed in class. It will be assigned on a weekly basis. The lowest two written homework grades will be dropped at the end of the semester before the final course grade is calculated. Written homework is due on the date assigned. Late written homework will not be accepted without a very good excuse.

Project

Students are also required to complete one project. A project consists of a written part and a poster presentation, as specified below. **The turn-in date for the written part (pdf, per email) is April 9, 2018, 9 am. Poster presentations will take place in the week 23-27 April. Projects will be assigned on March 12, 2018.** The written part of a project is a 5-10 page comprehensive summary a topic not covered in class. The poster is about the same topic and must be presented during class in conference style (about 15-20 minutes, including discussion). Specific instructions will be provided at the time the project is assigned. The instructor may ask the students for minor/major revisions of the written part of the project as needed. The written part of the project determines the grade for the project. However, the instructor reserves the right to reduce the project grade by any amount if the poster presentation in his assessment does not meet professional standards. **The project assignment (written part and poster) is teamwork: three students will form one team, and all students will receive the same grade for their project!** Teams will be formed at the time the project is assigned. It is at the discretion of the instructor to assign four students to one project –or two students to one project– if the course enrollment is not divisible by three.

Course Grades and Weights

- 30% Homework
- 10% Project
- 25% Mid-term exam
- 35% Final exam

A: 85-100; B: 70-85; C: 55-70; F: <55 (no D grade)

Academic Integrity Policy

The graduate academic integrity policy, as stated in the Graduate School Policy Handbook, applies. In addition, students may discuss homework problems with other students, but only in general terms. **Copying homework solutions from the web is strictly forbidden!**

The official statement on “Academic Integrity” reads: “As members of the Clemson University community, we have inherited Thomas Green Clemson's vision of this institution as a ‘high seminary of learning.’ Fundamental to this vision is a mutual commitment to truthfulness, honor, and responsibility, without which we cannot earn the trust and respect of others. Furthermore, we recognize that academic dishonesty detracts from the value of a Clemson degree. Therefore, we shall not tolerate lying, cheating, or stealing in any form. In instances where academic standards may have been compromised, Clemson University has a responsibility to respond appropriately to charges of violations of academic integrity."

Disability Access Statement

It is university policy to provide, on a flexible and individualized basis, reasonable accommodations to students who have disabilities. Students with disabilities requesting accommodations should make an appointment with Disability Services (656-6848), to discuss specific needs within the first month of classes. Students should present a Faculty Accommodation Letter from Student Disability Services when they meet with instructors. Accommodations are not retroactive and new Faculty Accommodation Letters must be presented each semester.

Clemson University Title IX (Sexual Harassment) Statement

Clemson University is committed to a policy of equal opportunity for all persons and does not discriminate on the basis of race, color, religion, sex, sexual orientation, gender, pregnancy, national origin, age, disability, veteran's status, genetic information or protected activity (e.g., opposition to prohibited discrimination or participation in any complaint process, etc.) in employment, educational programs and activities, admissions and financial aid. This includes a prohibition against sexual harassment and sexual violence as mandated by Title IX of the Education Amendments of 1972. The policy is located at http://www.clemson.edu/campus-life/campus-services/access/non-discrimination-policy.html. Alesia Smith serves as Clemson's Title IX Coordinator and he may be reached at knightl@clemson.edu or 656-3181.