PHYSICS

35 Sloane Physics Laboratory, 203.432.3605
http://physics.yale.edu
M.S., M.Phil., Ph.D.

Chair
Karsten Heeger

Director of Graduate Studies
Daisuke Nagai (daisuke.nagai@yale.edu)

Professors

Associate Professors
Damon Clark (Molecular, Cellular, & Developmental Biology), Walter Goldberger, Michael Murrell (Biomedical Engineering), Daisuke Nagai, Nikhil Padmanabhan, David Poland, Peter Rakich (Applied Physics), Alison Sweeney

Assistant Professors

Lecturers
Sidney Cahn, Mehdi Ghiassi-Nejad, Stephen Irons, Rona Ramos, Adriane Steinacker

FIELDS OF STUDY
Fields include atomic physics and quantum optics; nuclear physics; particle physics; astrophysics and cosmology; condensed matter; biological physics; quantum information physics; applied physics; and other areas in collaboration with the School of Engineering & Applied Science and the departments of Applied Physics; Astronomy;
Chemistry; Earth and Planetary Sciences; Molecular Biophysics and Biochemistry; and Molecular, Cellular, and Developmental Biology.

INTEGRATED GRADUATE PROGRAM IN PHYSICAL AND ENGINEERING BIOLOGY (PEB)

Students applying to the Ph.D. program in Physics may also apply to be part of the PEB program. See the description under Non-Degree-Granting Programs, Councils, and Research Institutes for course requirements, and http://peb.yale.edu for more information about the benefits of this program and application instructions.

SPECIAL REQUIREMENTS FOR THE PH.D. DEGREE

To complete the course requirements, students are expected to take a set of seven term courses: six foundational courses and one elective. The six core courses (PHYS 500, Advanced Classical Mechanics; PHYS 502, Electromagnetic Theory I; PHYS 506, Mathematical Methods of Physics; PHYS 508, Quantum Mechanics I; PHYS 510, Quantum Mechanics II; and PHYS 512, Statistical Physics I) serve to complete the student's undergraduate core training in classical and quantum physics. For the seventh course, students select from the list of graduate elective courses offered by the Physics or Applied Physics departments, or courses offered by other departments with the approval of the director of graduate studies (DGS). In addition, all students are required to engage in a research project by taking PHYS 990, Special Investigations. First-year students are also required, in addition to their core courses, to take PHYS 515, Topics in Modern Physics Research, in the fall, and PHYS 590, Responsible Conduct in Research for Physical Scientists, in the spring. Certain equivalent course work or successful completion of a pass-out examination may allow substitution of core courses for individual students.

A written qualifying event, taken by all students at the beginning of the third term, consists of four separate written components on Classical Mechanics, Electromagnetic Theory, Statistical Mechanics, and Quantum Mechanics. Students take each component; the components are marked and returned to the student, who is expected to correct any errors and resubmit in a week. For subjects the students have not yet encountered in graduate courses, the event serves as a pre-test. It is not a pass/fail exam, but rather a learning milestone. Students will also complete a qualifying event in research in conjunction with PHYS 990.

Students who have completed their course requirements with satisfactory grades (two Honors and an overall High Pass average), completed the qualifying events, and submitted an acceptable thesis prospectus to their core committee are recommended for admission to candidacy. Students must submit the thesis prospectus before the end of their third year of study.

There is no foreign language requirement, but students whose first language is not English must receive, at a minimum, 25 or above on the TOEFL speak test. Admitted students who fall below this threshold will be asked to take an ESL class prior to being able to teach. The teaching experience is regarded as an integral part of the graduate training program. During their studies, students are expected to serve four terms as teaching fellows, usually in the first two years. Students who require additional support
from the Graduate School must teach additional terms, if needed, after they have fulfilled this teaching requirement.

Formal association with a dissertation adviser normally begins after the fourth term, after the qualifying event has been passed and required course work has been completed. An adviser from a department other than Physics can be chosen in consultation with the DGS, provided the dissertation topic is deemed suitable for a physics Ph.D.

MASTER’S DEGREES

**M.Phil.** Students who have successfully advanced to candidacy qualify for the M.Phil. degree.

**M.S. (en route to the Ph.D.)** Students who complete all six core courses listed above, plus either PHYS 990, Special Investigations or an advanced elective (all with a satisfactory record) qualify for the M.S. degree. Certain equivalent course work or successful completion of a pass-out examination may allow individual students to substitute an elective course for a required one.

Program materials are available upon request to the Director of Graduate Studies, Department of Physics, Yale University, PO Box 208120, New Haven CT 06520-8120; email, stacey.watts@yale.edu (graduatephysics@yale.edu); website, http://physics.yale.edu.

COURSES

**PHYS 500a, Advanced Classical Mechanics**  Yoram Alhassid  

**PHYS 502b, Electromagnetic Theory I**  Nir Navon  
Classical electromagnetic theory including boundary-value problems and applications of Maxwell equations. Macroscopic description of electric and magnetic materials. Wave propagation.

**PHYS 504b, Modern Physics Measurements**  Staff  
A laboratory course with experiments and data analysis in soft and hard condensed matter, nuclear and elementary particle physics.

**PHYS 506a, Mathematical Methods of Physics**  Keith Baker  
Survey of mathematical techniques useful in physics. Includes vector and tensor analysis, group theory, complex analysis (residue calculus, method of steepest descent), differential equations and Green's functions, and selected advanced topics.

**PHYS 508a, Quantum Mechanics I**  Thomas Appelquist  
The principles of quantum mechanics with application to simple systems. Canonical formalism, solutions of Schrödinger's equation, angular momentum, and spin.

**PHYS 515a, Topics in Modern Physics Research**  Nir Navon  
A comprehensive introduction to the various fields of physics research carried out in the department and a formal introduction to scientific reading, writing, and presenting.
PHYS 517b / ENAS 517b / MB&B 517b / MCDB 517b, Methods and Logic in Interdisciplinary Research  Corey O’Hern
This half-term PEB class is intended to introduce students to integrated approaches to research. Each week, the first of two sessions is student-led, while the second session is led by faculty with complementary expertise and discusses papers that use different approaches to the same topic (for example, physical and biological or experiment and theory). Counts as 0.5 credit toward graduate course requirements. ½ Course cr

PHYS 524a, Introduction to Nuclear Physics  David Moore
An introduction to a wide variety of topics in nuclear physics and related experimental techniques including weak interactions, neutrino physics, neutrinoless double beta decay, and relativistic heavy-ion collisions. The aim is to give a broad perspective on the subject and to develop the key ideas in simple ways, with more weight on physics ideas than on mathematical formalism. The course assumes no prior knowledge of nuclear physics and only elementary quantum mechanics. It is accessible to advanced undergraduates.

PHYS 538a, Introduction to Relativistic Astrophysics and General Relativity  Walter Goldberger
Basic concepts of differential geometry (manifolds, metrics, connections, geodesics, curvature); Einstein’s equations and their application to such areas as cosmology, gravitational waves, black holes.

PHYS 548a, Solid State Physics I  Sohrab Ismail-Beigi
A two-term sequence (with PHYS 549) covering the principles underlying the electrical, thermal, magnetic, and optical properties of solids, including crystal structures, phonons, energy bands, semiconductors, Fermi surfaces, magnetic resonance, phase transitions, and superconductivity.

PHYS 549b, Solid State Physics II  Yu He
A two-term sequence (with PHYS 548) covering the principles underlying the electrical, thermal, magnetic, and optical properties of solids, including crystal structures, phonons, energy bands, semiconductors, Fermi surfaces, magnetic resonance, phase transitions, and superconductivity.

PHYS 601a / APHY 660a, Quantum Information and Computation  Shruti Puri
This course focuses on the theory of quantum information and computation. We cover the following tentative list of topics: overview of postulates of quantum mechanics and measurements, quantum circuits, physical implementation of quantum operations, introduction to computational complexity, quantum algorithms (DJ, Shor’s, Grover’s, and others as time permits), decoherence and noisy quantum channels, quantum error-correction and fault-tolerance, stabilizer formalism, error-correcting codes (Shor, Steane, surface-code, and others as time permits), quantum key distribution, quantum Shannon theory, entropy and data compression.

PHYS 609a, Relativistic Field Theory I  Ian Moult
The fundamental principles of quantum field theory. Interacting theories and the Feynman graph expansion. Quantum electrodynamics including lowest order processes, one-loop corrections, and the elements of renormalization theory.

PHYS 628a / APHY 628a, Statistical Physics II  Benjamin Machta
An advanced course in statistical mechanics. Topics may include mean field theory of and fluctuations at continuous phase transitions; critical phenomena, scaling, and
introduction to the renormalization group ideas; topological phase transitions; dynamic correlation functions and linear response theory; quantum phase transitions; superfluid and superconducting phase transitions; cooperative phenomena in low-dimensional systems.

**PHYS 632a, Quantum Many-Body Theory II**  
Meng Cheng  
A second course in quantum many-body theory, covering the core physics of electron systems, with emphasis on the electron-electron interaction, on the role of dimensionality, on the coupling either to magnetic impurities leading to the well-known Kondo effect or to the electromagnetic noise. Applications to mesoscopic systems and cold atomic gases are also developed.

**PHYS 675a / APHY 675a, Principles of Optics with Applications**  
Hui Cao  
Introduction to the principles of optics and electromagnetic wave phenomena with applications to microscopy, optical fibers, laser spectroscopy, nanophotonics, plasmonics, and metamaterials. Topics include propagation of light, reflection and refraction, guiding light, polarization, interference, diffraction, scattering, Fourier optics, and optical coherence.

**PHYS 677a / APHY 677a, Noise, Dissipation, Amplification, and Information**  
Michel Devoret  
Graduate-level non-equilibrium statistical physics applied to noise phenomena, both classical and quantum. The aim of the course is to explain the fundamental link between the random fluctuations of a physical system in steady state and the response of the same system to an external perturbation. Several key examples in which noise appears as a resource rather than a limitation are treated: spin relaxation in nuclear magnetic resonance (motional narrowing), Johnson-Nyquist noise in solid state transport physics (noise thermometry), photon correlation measurements in quantum optics (Hanbury Brown-Twiss experiment), and so on. The course explores both passive and active systems. It discusses the ultimate limits of amplifier sensitivity and speed in physics measurements.

**PHYS 816b / APHY 816b, Techniques of Microwave Measurement and RF Design**  
Robert Schoelkopf  
An advanced course covering the concepts and techniques of radio-frequency design and their application in making microwave measurements. The course begins with a review of lumped element and transmission line circuits, network analysis, and design of passive elements, including filters and impedance transformers. We continue with a treatment of passive and active components such as couplers, circulators, amplifiers, and modulators. Finally, we employ this understanding for the design of microwave measurement systems and techniques for modulation and signal recovery, to analyze the performance of heterodyne/homodyne receivers and radiometers.

**PHYS 990a, Special Investigations**  
Bonnie Fleming  
Directed research by arrangement with individual faculty members and approved by the DGS. Students are expected to propose and complete a term-long research project. The culmination of the project is a presentation that fulfills the departmental requirement for the research qualifying event.
PHY 991a / ENAS 991a / MB&B 591a / MCDB 591a, Integrated Workshop  Corey O’Hern

This required course for students in the PEB graduate program involves a series of modules, co-taught by faculty, in which students from different academic backgrounds and research skills collaborate on projects at the interface of physics, engineering, and biology. The modules cover a broad range of PEB research areas and skills. The course starts with an introduction to MATLAB, which is used throughout the course for analysis, simulations, and modeling.