PHYSICS

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

Chair
Karsten Heeger

Director of Graduate Studies
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Professors Charles Ahn (*Applied Physics*), Yoram Alhassid, Thomas Appelquist, Charles Bailyn (*Astronomy*), O. Keith Baker, Charles Baltay (*Emeritus*), Sean Barrett, Joerg Bewersdorf (*Cell Biology*), Helen Caines, Hui Cao (*Applied Physics*), Richard Casten (*Emeritus*), Flavio Cavanna (*Adjunct*), Paolo Coppi (*Astronomy*), Sarah Demers, Michel Devoret (*Applied Physics*), Thierry Emonet (*Molecular, Cellular, and Developmental Biology*), Paul Fleury (*Emeritus*), Marla Geha (*Astronomy*), Steven Girvin, Larry Gladney, Leonid Glazman, Walter Goldberger, Jack Harris, John Harris (*Emeritus*), Karsten Heeger, Victor Henrich (*Emeritus*), Jonathon Howard (*Molecular Biophysics and Biochemistry*), Francesco Iachello (*Emeritus*), Sohrab Ismaill-Beigi (*Applied Physics*), Steve Lamoreaux, Andre Levchenko (*Biomedical Engineering*), Reina Maruyama, Simon Mochrie, Vincent Moncrief, Daisuke Nagai, Priyamvada Natarajan (*Astronomy*), Andrew Neitzke (*Mathematics*), Corey O'Hern (*Mechanical Engineering and Materials Science*), Vidvus Ozolins (*Applied Physics*), Ornella Palamara (*Adjunct*), Peter Parker (*Emeritus*), Daniel Prober (*Applied Physics*), Nicholas Read, Peter Schiffer (*Applied Physics*), Robert Schoelkopf (*Applied Physics*), John Schotland (*Mathematics*), Jurgen Schukraft (*Adjunct*), Ramamurti Shankar, Witold Skiba, A. Douglas Stone (*Applied Physics*), Hong Tang (*Engineering*), Paul Tipton, Thomas Ullrich (*Adjunct*), C. Megan Urry, Frank van den Bosch (*Astronomy*), Pieter van Dokkum (*Astronomy*), John Wettlaufer (*Earth and Planetary Sciences*), Robert Wheeler (*Emeritus*), Werner Wolf (*Emeritus*), Michael Zeller (*Emeritus*)

Associate Professors Damon Clark (*Molecular, Cellular, and Developmental Biology*), David C. Moore, Michael Murrell (*Biomedical Engineering*), Nikhil Padmanabhan, David Poland, Peter Rakich (*Applied Physics*), Alison Sweeney

Assistant Professors Charles Brown, Meng Cheng, Eduardo da Silva Neto, Yu He (*Applied Physics*), Benjamin Machta, Owen Miller (*Applied Physics*), Ian Moult, Nir Navon, Laura Newburgh, Shruti Puri (*Applied Physics*), Diana Qiu (*Mechanical Engineering and Materials Science*)

Lecturers Sidney Cahn, Mehdi Ghiassi-Nejad, Caitlin Hansen, Stephen Irons, Steven Konezny, 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 full-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 for the substitution or waiver of core courses for individual students.

All students must participate in a two-part qualifying event by their second year of study. Part one is a qualifying event in research consisting of an oral presentation on their research completed during PHYS 990, Special Investigation. Part two is a written qualifying event, taken by all students at the beginning of the third term, consisting 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 may take the written qualifying event before the research qualifying event. Both events must be completed by the end of the student's second year.

Before the end of students' third year of study, they must submit their thesis prospectus, as presented to and approved by their core thesis committee. Students who have completed their required course credits with satisfactory grades (two Honors and an overall High Pass average), taken the qualifying events, and submitted an acceptable thesis prospectus are recommended for admission to candidacy and to receive their M.Phil en route. Students entering the program with a master's degree in physics or a related field may waive equivalent graduate-level core courses, with approval from the DGS, without the requirement of replacing course credits. These student can advance to candidacy, after completing all other requirements, without receiving an M.Phil from the department.

There is no foreign language requirement in the physics program, 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 required 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. Students who withdraw from the Ph.D. program may be eligible to receive the M.S. degree if they have met the requirements and have not already received the M.Phil. degree. For the M.S., students must successfully complete all six core courses listed above, in addition to completing either PHYS 990, Special Investigations, or an advanced elective (all with a satisfactory record). 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).

COURSES

PHYS 500a, Advanced Classical Mechanics Yoram Alhassid
Newtonian dynamics, Lagrangian dynamics, and Hamiltonian dynamics. Rigid bodies and Euler equations. Oscillations and eigenvalue equations. Classical chaos. Introduction to dynamics of continuous systems.

PHYS 502b, Electromagnetic Theory I Walter Goldberger
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 Laura Newburgh and Sidney Cahn
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 Walter Goldberger
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 510b, Quantum Mechanics II Meng Cheng
Approximation methods, scattering theory, and the role of symmetries. Relativistic wave equations. Second quantized treatment of identical particles. Elementary introduction to quantized fields.

PHYS 512b, Statistical Physics I Yoram Alhassid
Review of thermodynamics, the fundamental principles of classical and quantum statistical mechanics, canonical and grand canonical ensembles, identical particles, Bose and Fermi statistics, phase transitions and critical phenomena, enormalization group, irreversible processes, fluctuations.

PHYS 515a, Topics in Modern Physics Research Charles Brown and Karsten Heeger
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 and Emma Carley
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 522a, Introduction to Atomic Physics Nir Navon
The course is intended to develop basic theoretical tools needed to understand current research trends in the field of atomic physics. Emphasis is given to laser-spectroscopic methods including laser cooling and trapping. Experimental techniques discussed when appropriate.

PHYS 523a / CB&B 523a / ENAS 541a / MB&B 523a, Biological Physics Yimin Luo
The course has two aims: (1) to introduce students to the physics of biological systems and (2) to introduce students to the basics of scientific computing. The course focuses on studies of a broad range of biophysical phenomena including diffusion, polymer statistics, protein folding, macromolecular crowding, cell motion, and tissue development using computational tools and methods. Intensive tutorials are provided for MATLAB including basic syntax, arrays, for-loops, conditional statements, functions, plotting, and importing and exporting data.

PHYS 524a, Introduction to Nuclear Physics Reina Maruyama
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 526b, Introduction to Elementary Particle Physics David Poland
An overview of particle physics, including an introduction to the standard model, experimental techniques, symmetries, conservation laws, the quark-parton model, and open questions in particle physics.

PHYS 548a / APHY 548a / ENAS 850a, Solid State Physics I Yu He
A two-term sequence (with APHY 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 / APHY 549b / ENAS 851b, Solid State Physics II Sohrab Ismail-Beigi
A two-term sequence (with APHY 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 561a / MB&B 561a / MCDB 561a, Modeling Biological Systems I Thierry Emonet
Biological systems make sophisticated decisions at many levels. This course explores the molecular and computational underpinnings of how these decisions are made, with a focus on modeling static and dynamic processes in example biological systems. This course is aimed at biology students and teaches the analytic and computational methods needed to model genetic networks and protein signaling pathways. Students present and discuss original papers in class. They learn to model using MatLab in a series of in-class hackathons that illustrate the biological examples discussed in the lectures. Biological systems and processes that are modeled include: (i) gene expression, including the kinetics of RNA and protein synthesis and degradation; (ii) activators and repressors; (iii) the lysogeny/lysis switch of lambda phage; (iv) network motifs and how they shape response dynamics; (v) cell signaling, MAP kinase networks and cell fate decisions; and (vi) noise in gene expression. Prerequisites: MATH 115 or 116, BIOL 101–104, or with permission of instructors. This course also benefits students who have taken more advanced biology courses (e.g. MCDB 200, MCDB 310, MB&B 300/301).

PHYS 562b / AMTH 765b / CB&B 562b / ENAS 561b / INP 562b / MB&B 562b / MCDB 562b, Modeling Biological Systems II Joe Howard
This course covers advanced topics in computational biology. How do cells compute, how do they count and tell time, how do they oscillate and generate spatial patterns? Topics include time-dependent dynamics in regulatory, signal-transduction, and neuronal networks; fluctuations, growth, and form; mechanics of cell shape and motion; spatially heterogeneous processes; diffusion. This year, the course spends roughly half its time on mechanical systems at the cellular and tissue level, and half on models of neurons and neural systems in computational neuroscience. Prerequisite: a 200-level biology course or permission of the instructor.

PHYS 570b / ASTR 570b, High-Energy Astrophysics Paolo Coppi
A survey of current topics in high-energy astrophysics, including accreting black hole and neutron star systems in our galaxy, pulsars, active galactic nuclei and relativistic

jets, gamma-ray bursts, and ultra-high-energy cosmic rays. The basic physical processes underlying the observed high-energy phenomena are also covered.

PHYS 600a / ASTR 600a, Cosmology Nikhil Padmanabhan
A comprehensive introduction to cosmology at the graduate level. The standard paradigm for the formation, growth, and evolution of structure in the universe is covered in detail. Topics include the inflationary origin of density fluctuations; the thermodynamics of the early universe; assembly of structure at late times and current status of observations. The basics of general relativity required to understand essential topics in cosmology are covered. Advanced undergraduates may register for the course with permission of the instructor.

PHYS 603a, Euclidean-Signature Semi-Classical Analysis for Quantum Mechanics and Quantum Field Theory Vincent Moncrief
The textbook WKB (or semi-classical) approach to solving quantum eigenvalue problems has been significantly improved and generalized in scope in recent years. New techniques offer advantages, not only over the very circumscribed, classical WKB (Wentzel, Kramers, Brillouin) methods (which are mostly limited to elementary, one dimensional quantum mechanical problems), but also over conventional perturbation theory. The corresponding "Euclidean-Signature Semi-Classical Program" is undergoing rapid, continuing development and has significant applications, not only to higher dimensional quantum mechanical problems but also to interacting quantum field theories. Unlike conventional perturbation theory this approach does not require the decomposition of a quantum Hamiltonian operator into a solvable (e.g., free field) component and its "perturbation" and, in the case of gauge theories, can maintain full, non-abelian gauge invariance at every order of a calculation. Prerequisite: PHYS 440 or 441. A basic understanding of textbook perturbation theory and WKB techniques is strongly advised. The methods developed in this course build on and revise both of these fundamental techniques of quantum approximation theory.

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 610b / APHY 610b, Quantum Many-Body Theory Leonid Glazman
Identical particles and second quantization. Electron tunneling and spectral function. General linear response theory. Approximate methods of quantum many-body theory. Dielectric response, screening of long-range interactions, electric conductance, collective modes, and photon absorption spectra. Fermi liquid; Cooper and Stoner instabilities; notions of superconductivity and magnetism. BCS theory, Josephson effect, and Majorana fermions in condensed matter; superconducting qubits. Bose-Einstein condensation; Bogoliubov quasiparticles and solitons.

PHYS 624b, Group Theory Witold Skiba
Lie algebras, Lie groups, and some of their applications. Representation theory. Explicit construction of finite-dimensional irreducible representations. Invariant operators and their eigenvalues. Tensor operators and enveloping algebras. Boson and fermion realizations. Differential realizations. Quantum dynamical applications.

PHYS 628a / APHY 628a, Statistical Physics II Meng Cheng
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 630b, Relativistic Field Theory II Ian Moult
An introduction to non-Abelian gauge field theories, spontaneous symmetry breakdown, and unified theories of weak and electromagnetic interactions. Renormalization group methods, quantum chromodynamics, and nonperturbative approaches to quantum field theory.

PHYS 633b / APHY 633b, Introduction to Superconductivity Yu He
The fundamentals of superconductivity, including both theoretical understandings of basic mechanism and description of major applications. Topics include historical overview, Ginzburg-Landau (mean field) theory, critical currents and fields of type II superconductors, BCS theory, Josephson junctions and microelectronic and quantum-bit devices, and high-Tc oxide superconductors.

PHYS 634a / APHY 634a, Mesoscopic Physics I Michel Devoret
Introduction to the physics of nanoscale solid state systems, which are large and disordered enough to be described in terms of simple macroscopic parameters like resistance, capacitance, and inductance, but small and cold enough that effects usually associated with microscopic particles, like quantum-mechanical coherence and/or charge quantization, dominate. Emphasis is placed on transport and noise phenomena in the normal and superconducting regimes.

PHYS 635a, Quantum Entanglement in HEP Keith Baker
Basic principles and applications of quantum entanglement and quantum information science at GeV to TeV energies in particle and nuclear physics are covered. Topics include: quantum superposition, quantum entanglement, entanglement entropy, quantum computing, quantum algorithms, Bell's inequality tests, and quantum sensors.

PHYS 650a / APHY 650a, Theory of Solids I Leonid Glazman

PHYS 670a, Special Topics in Biophysics Benjamin Machta
The aim of the course is to introduce students to the approaches, methods, major results, and open questions in modern biological physics. Topics include non-equilibrium statistical physics, with applications to kinetic proof-reading and understanding molecular motors, information theory with applications to cellular signaling and phase transitions as they occur in living systems. The course is designed for graduate students in physics or a closely related field, otherwise, permission of the instructor is required.

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 676a / APHY 676a, Introduction to Light-Matter Interactions Peter Rakich
Optical properties of materials and a variety of coherent light-matter interactions are explored through the classical and quantum treatments. The role of electronic, phononic, and plasmonic interactions in shaping the optical properties of materials is examined using generalized quantum and classical coupled-mode theories. The dynamic response of media to strain, magnetic, and electric fields is also treated. Modern topics are explored, including optical forces, photonic crystals, and metamaterials; multi-photon absorption; and parametric processes resulting from electronic, optomechanical, and Raman interactions.

PHYS 678b, Computing for Scientific Research Larry Gladney
This hands-on lab course introduces students to essential computational and data analysis methods, tools, and techniques and their applications to solve problems in physics. The course introduces some of the most important and useful skills, concepts, methods, tools, and relevant knowledge to get started in scientific research broadly defined, including theoretical, computational, and experimental research. Students learn basic programming in Python, data analysis, statistical tools, modeling, simulations, machine learning, high-performance computing, and their applications to problems in physics and beyond.

PHYS 679a, Nonlinear Optics and Lasers
Fundamental principles of nonlinear optics and lasers. Nonlinear optical susceptibilities; wave propagation and coupling in nonlinear media; harmonic, sum, and difference frequency generation; parametric amplification and oscillation; phase conjugation via four-wave mixing; self-phase modulation and solitons. Stimulated and spontaneous emission, interaction of two-level atoms with light, optical amplification. Optical resonators and threshold conditions for laser oscillation. Semiclassical laser theory, nonlinear and multi-mode lasing. Noise and quantum effects in lasers (time permitting).

PHYS 691a / APHY 691a, Quantum Optics Shruti Puri
Quantization of the electromagnetic field, coherence properties and representation of the electromagnetic field, quantum phenomena in simple nonlinear optics, atom-field interaction, stochastic methods, master equation, Fokker-Planck equation, Heisenberg-Langevin equation, input-output formulation, cavity quantum electrodynamics, quantum theory of laser, trapped ions, light forces, quantum optomechanics, Bose-Einstein condensation, quantum measurement and control.

PHYS 990a or b, Special Investigations Staff
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.

PHYS 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.