APPLIED PHYSICS

Becton Center, 203.432.2210
http://appliedphysics.yale.edu
M.S., M.Phil., Ph.D.

Chair
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Associate Professors Michael Choma (Biomedical Engineering), Peter Rakich

Assistant Professors Yu He, Owen Miller, Shruti Puri

FIELDS OF STUDY

Fields include areas of theoretical and experimental condensed-matter and materials physics, optical and laser physics, quantum engineering, and nanoscale science. Specific programs include surface and interface science, first principles electronic structure methods, photonic materials and devices, complex oxides, magnetic and superconducting artificially engineered systems, quantum computing and superconducting device research, nanotube physics, quantum optics, and random lasers.

INTEGRATED GRADUATE PROGRAM IN PHYSICAL AND ENGINEERING BIOLOGY (PEB)

Students applying to the Ph.D. program in Applied 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

The student plans a course of study in consultation with faculty advisers (the student’s advisory committee). There are a minimum of five core courses, two electives, and two Special Investigations (APHY 990), for a total of nine graded term courses. Core courses will be chosen from four groups: two from the CM group, and one from each of the other groups. Quantum Mechanics I (PHYS 508), Quantum Mechanics II (PHYS 510), and Electromagnetic Theory I (PHYS 502) will be default courses from their groups, with place-up option to others in the QM and E&M groups based on passing the Physics department exam. There will be no placing out of the required seven courses, except for incoming students with master’s or equivalent degrees, who are allowed to place out of three core courses.

The core groups are as follows:

Group 1 (QM, two courses required): Quantum Mechanics I (PHYS 508); Quantum Mechanics II (PHYS 510); Quantum Information and Computation (APHY 601); Quantum Optics (APHY 691).

Group 2 (E&M, one course required): Electromagnetic Theory I (PHYS 502); Principles of Optics with Applications (APHY 675); Techniques of Microwave Measurement and RF Design (APHY 816).

Group 3 (CM Physics, one course required): Solid State Physics I (APHY 548); Solid State Physics II (APHY 549); Statistical Physics I (PHYS 512); Introduction to Light-Matter Interactions (APHY 676).

Group 4 (one course required): Mathematical Methods of Physics (PHYS 506); Solid State Physics II (APHY 549); Principles of Optics with Applications (APHY 675); Noise, Dissipation, Amplification, and Information (APHY 677).

* PHYS 508, PHYS 510, and PHYS 502 are default courses requiring place-up exam in order to choose other courses from these groups.

Any of the courses from these groups not taken to meet core requirements may be taken as electives. Students who place up from a required course and prefer not to take any of the other courses in that group to satisfy the core requirement may petition the director of graduate studies (DGS) to substitute a different elective. Electives may be widely chosen, but will typically come from the following: Mesoscopic Physics I (APHY 634); Introduction to Superconductivity (APHY 633); Quantum Many-Body Theory (APHY 610); Nonlinear Optics and Lasers (APHY 679); Biological Physics (PHYS 533). Students may also petition the DGS to substitute an elective not on the standard list. The required seven courses are just the minimum, and students are strongly encouraged to take additional courses that are centrally related to their Ph.D. research. The DGS will work with students and their advisers to ensure that students are prepared for success in their field of research.
Students must take Responsible Conduct in Research for Physical Scientists (APHY 590), which discusses ethics and responsible conduct in scientific research and fulfills the requirement stipulated by the National Science Foundation for all students and for all postdoctoral researchers funded by the NSF. Note that APHY 590 may not be used to fulfill the nine-course requirement.

Each term, the faculty review the overall performance of the student and report their findings to the DGS, who determines whether the student may continue toward the Ph.D. degree. By the end of the second term, it is expected that a faculty member has agreed to accept the student as a research assistant. By December 5 of the third year, an area examination must be passed and a written prospectus submitted before dissertation research is begun. These events result in the student's admission to candidacy. Subsequently, the student will report orally each year to the full advisory committee on progress. When the research is nearing completion, but before the thesis writing has commenced, the full advisory committee will advise the student on the thesis plan. A final oral presentation of the dissertation research is required to be given during term time.

There is no foreign language requirement.

Teaching experience is regarded as an integral part of the graduate training program at Yale University, and all Applied Physics graduate students are required to serve as teaching fellows for two terms, typically during years two and three. Teaching duties normally involve assisting in laboratories or discussion sections and grading papers and are not expected to require more than ten hours per week. Students are not permitted to teach during the first year of study. Students who require additional support from the Graduate School must teach for up to an additional two terms, if needed.

If a student was admitted to the program having earned a score of less than 26 on the Speaking Section of the Internet-based TOEFL, the student will be required to take an English as a Second Language (ESL) course each term at Yale until the Graduate School’s Oral English Proficiency standard has been met. This must be achieved by the end of the third year in order for the student to remain in good standing.

HONORS REQUIREMENT

Students must meet the Graduate School’s Honors requirement in at least two term courses (excluding Special Investigations) by the end of the third term of full-time study. An extension of one term may be granted on a case-by-case basis at the discretion of the DGS, in consultation with the student’s committee.

MASTER’S DEGREES

M.Phil. See Degree Requirements under Policies and Regulations.

M.S. (en route to the Ph.D.) To qualify for the M.S., the student must pass eight term courses; no more than two may be Special Investigations. An average grade of at least High Pass is required, with at least one grade of Honors.

Terminal Master’s Degree Program Students may also be admitted directly to a terminal master’s degree program. The requirements are the same as for the M.S. en route to the Ph.D., although there are no core course requirements for students in this program. This program is normally completed in one year, but a part-time program may be spread over as many as four years. Some courses are available in the evening, to suit the needs of students from local industry.

Program materials are available upon request to the Director of Graduate Studies, Department of Applied Physics, Yale University, PO Box 208267, New Haven CT 06520-8267; email, applied.physics@yale.edu; website, http://appliedphysics.yale.edu.

COURSES

APHY 506a, Basic Quantum Mechanics Sohrab Ismail-Beigi
Basic concepts and techniques of quantum mechanics essential for solid state physics and quantum electronics. Topics include the Schrödinger treatment of the harmonic oscillator, atoms and molecules and tunneling, matrix methods, and perturbation theory.

APHY 548a, Solid State Physics I Yu He
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.

APHY 549b, Solid State Physics II Vidvuds Ozolins
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.

APHY 588a, Modern Nanophotonics: Theory and Design Owen Miller
This course is an introduction to modern nanophotonic theory and design. We introduce a broad range of mathematical and computational tools with which one can analyze, understand, and design for a diverse range of nanophotonic phenomena. The course is meant to be in the orthogonal complement of traditional courses working through Jackson’s Classical Electrodynamics—we (mostly) avoid specialized high-symmetry cases in which Maxwell’s equations can be solved exactly. Instead, our emphasis is on general mode, quasinormal-mode, and scattering-matrix descriptions, as well as surface- and volume-integral formulations that distill the essential physics of complex systems. The unique properties and trade-offs for a variety of computational methods, including finite-element, finite-difference, integral-equation, and modal-expansion (e.g., RCWA) approaches, comprise a significant portion of the latter half
of the term. The robust open-source computational tools Meep, S4, and NLopt are introduced early on, to be learned and utilized throughout the term. Prerequisites: undergraduate-level electromagnetism (e.g., APHY 322) and linear algebra (e.g., MATH 222 or 225); familiarity with any of Matlab/Python/Julia/etc., or a willingness to learn.

**APHY 607b, Modern Topics in Optics and Quantum Electronics** Peter Rakich
This course provides a survey of modern topics involving integrated photonics, optomechanics, nonlinear optics, and laser physics for students interested in contemporary experimental optics research. Subjects include nonlinear wave phenomena, optomechanical interactions, phonon physics, light scattering, light emission and detection, cavities, systems of cavities, traveling-wave devices and interactions, perturbation theory, reciprocal and nonreciprocal systems, parametric interactions, laser oscillators and related technologies. Students are encouraged to explore these and related research topics through independent study and classroom presentations.

**APHY 610b / PHYS 610b, Quantum Many-Body Theory** Leonid Glazman

**APHY 628a / PHYS 628a, Statistical Physics II** Leonid Glazman
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.

**APHY 633b / PHYS 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.

**APHY 634a / PHYS 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.

**APHY 675a / PHYS 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.

**APHY 676a / PHYS 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.

**APHY 691a / PHYS 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.

**APHY 990a or b, Special Investigations** Vidvuds Ozolins
Faculty-supervised individual projects with emphasis on research, laboratory, or theory. Students must define the scope of the proposed project with the faculty member who has agreed to act as supervisor, and submit a brief abstract to the director of graduate studies for approval.