APPLIED PHYSICS

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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 science, quantum information, 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, quantum transport, 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 requirements for a Ph.D. in applied physics include passing at least nine course units. Courses such as Dissertation Research, Master's Thesis, or seminars do not count towards the nine-course requirement, but two terms of Special Investigation courses are acceptable. Other than the Special Investigation courses, the courses counting toward the nine-course requirement must be full-credit graduate courses. Courses outside of those identified as acceptable in the departmental degree guidelines must have a clear technical, scientific, or mathematical focus that is related to applied physics in the judgement of the student's adviser and the DGS.

Within the nine-course requirement, students must pass the three core courses, unless they are substituted or waived with approval by the DGS. The three core courses are Electromagnetic Theory I (PHYS 502), Quantum Mechanics I (PHYS 508), and Statistical Physics I (PHYS 512).

Students must also take the Research in Applied Physics Seminar (APHY 576) and the Responsible Conduct in Research for Physical Scientists Seminar (APHY 590).

Students typically complete most of their course requirements in the first year, and sufficient progress toward meeting the course requirements is necessary to remain in good standing in the program. Note that the required courses are just the minimum, and students are strongly encouraged to consult with their adviser about taking additional courses that are needed to facilitate their dissertation research.

By the end of the first year, students must find a research adviser who is willing to supervise a project that is consonant with the research program of that faculty. Research advisers must have an appointment in the graduate school and be engaged in research that falls broadly within the subject of applied physics, although they do not need to be members of the department's faculty.

After completing coursework, the next step toward a degree is admission to candidacy, indicating that the student is prepared to do original and independent research. To be admitted to candidacy, students must submit a written research prospectus and pass an area examination early in their third year. If a student has faced unusual circumstances, this deadline can be extended, with the support of the research adviser and approval of the DGS.

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. Teaching duties 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

In order to remain in good standing in the program, students are expected make steady progress in meeting their course requirements and to obtain Honors grades in at least two full-term courses by the end of their fourth term of full-time study. Courses such as Master's Thesis, seminars, or Special Investigations cannot be used to fulfill the requirement for two Honors grades. An extension may be granted on a case-by-case basis at the discretion of the DGS, in consultation with the student's adviser. Students are also expected to maintain an average grade of High Pass during their time at Yale, following the averaging methodology determined by the graduate school.

MASTER'S DEGREES

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

M.S. Students may apply for a terminal master's degree in applied physics. For the M.S. degree, the requirements are that the student pass eight full-credit graduate courses (not seminars), typically courses similar to those that would meet the course requirements for the Ph.D. No more than two of the courses may be Special Investigations. Students may substitute other graduate courses with a clear technical, scientific, or mathematical focus that is related to applied physics in the judgement of the student's adviser and the DGS. An average grade of at least High Pass is required, with at least one grade of Honors. This terminal degree program is normally completed in one year. Doctoral students who withdraw from the Ph.D. program may be eligible to receive the M.S. if they have met the above requirements and have not already received the M.Phil.

Program materials are available upon e-mail request to applied.physics@yale.edu, or at http://appliedphysics.yale.edu.

COURSES

APHY 506a, Basic Quantum Mechanics John Sous
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 526a, Explorations in Physics and Computation Logan Wright
Computation has taken on an important, often central, role in both the practice and conception of physical science and engineering physics. This relationship is intricate and multifaceted, including computation for physics, computation with physics, and computation as a lens through which to understand physical processes. This course takes a more or less random walk within this space, surveying ideas and technologies that either apply computation to physics, that understand physical phenomena through the lens of computation, or that use physics to perform computation. Given the extent to which machine learning methods are currently revolutionizing this space of ideas, we focus somewhat more on topics related to modern machine learning, as opposed to other sorts of algorithms and computation. Since it is covered more deeply in other courses, we do not extensively cover error-corrected/fault tolerant quantum information processing, but we do frequently consider quantum physics. The course does not provide a systematic overview of any one topic, but rather a sampling of ideas and concepts relevant to modern research challenges. It is therefore intended for graduate students in early years of their program or research-inclined senior undergraduate students contemplating a research career. As a result, in addition to the scientific topics at hand, key learning goals include the basics of literature review, presentation, collegial criticism (peer review), and synthesizing new research ideas. Evaluation is primarily through two projects, one a lecture reviewing a topic area of

interest and one a tutorial notebook providing worked numerical examples/code meant to develop or introduce a concept. Prior experience with Python is ideal, but can be learned as part of the coursework. Students should ideally be familiar with quantum mechanics, including density matrices and some phase-space methods, but this applies to only small fraction of the course. The course is primarily a survey-level overview of many topics, not a deep dive into any one topic. As a result, students who have extensive background on many of the topics described in the syllabus are welcome to participate but should speak with the instructor beforehand so we can determine if their learning goals can be met.

APHY 548a / ENAS 850a / PHYS 548a, Solid State Physics I Vidvuds Ozolins
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.

APHY 549b / ENAS 851b / PHYS 549b, Solid State Physics II 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 576a, Topics in Applied Physics Research Peter Rakich
The course introduces the fundamentals of applied physics research to graduate students in the Department of Applied Physics in order to introduce them to resources and opportunities for research activities. The content of the class includes overview presentations from faculty and other senior members of the department and related departments about their research and their career trajectories. The class also includes presentations from campus experts who offer important services that support Applied Physics graduate students in their successful degree completion.

APHY 588b, 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 590b / PHYS 590b, Responsible Conduct in Research for Physical Scientists Karsten Heeger
A review and discussion of best practices of conduct in research including scientific integrity and misconduct; mentorship; data management; and diversity, equity, and inclusion in science.

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
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.

APHY 628b / PHYS 628b, Statistical Physics II Nicholas Read
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 650a / PHYS 650a, Theory of Solids I Leonid Glazman
A graduate-level introduction with focus on advanced and specialized topics. Knowledge of advanced quantum mechanics (Sakurai level) and solid state physics (Kittel and Ashcroft-Mermin level) is assumed. The course teaches advanced solid state physics techniques and concepts.

APHY 660a / PHYS 601a, Quantum Information and Computation Aleksander Kubica
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.

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 725a / ENAS 725a, Advanced Synchrotron Techniques and Electron Spectroscopy of Materials Charles Ahn
This course provides descriptions of advanced concepts in synchrotron X-ray and electron-based methodologies for studies of a wide range of materials at atomic and nano-scales. Topics include X-ray and electron interactions with matter, X-ray scattering and diffraction, X-ray spectroscopy and inelastic methods, time-resolved applications, X-ray imaging and microscopy, photo-electron spectroscopy, electron microscopy and spectroscopy, among others. Emphasis is on applying the fundamental knowledge of these advanced methodologies to real-world materials studies in a variety of scientific disciplines.

APHY 816a / PHYS 816a, 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.

APHY 990a or b, Special Investigations Peter Rakich
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.