Physics

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Program of Study

Physics is concerned with the study of matter, energy, forces, and their interaction in the world and universe around us. The undergraduate curriculum in the Department of Physics leading to the B.A. in physics includes a strong emphasis on lab experiment and covers the broad fundamentals necessary for graduate study in theoretical physics, experimental physics, or astronomy and astrophysics, as well as some fields of engineering and many interdisciplinary specialties requiring a strong technical background (e.g., biophysics, medical physics, atmospheric and environmental sciences).

Program Requirements

Courses. For students starting physics course work in 2000 or later, concentration requirements are in effect as described in the rest of this section. The revised curriculum leading to the B.A. degree in physics is designed for maximum flexibility consistent with a thorough coverage of the essential principles of physics. Degree requirements include introductory and advanced physics and mathematics courses, as well as concentration electives that allow students to pursue specific interests. Students who will pursue graduate work in astrophysics should consider the concentration program leading to a B.A. in physics with a specialization in astrophysics, which is described in a later section.

Students who plan to concentrate in physics are encouraged to start course work in their first year. However, the concentration requirements can be completed in three years, so one could start physics in the second year and still complete the program. Two of the physics and two of the mathematics courses can be designated as general education courses, with fourteen courses remaining to fulfill the concentration.

In general, students should take the most advanced courses for which they have the appropriate prerequisites. Entering students will be given a placement for General Physics I (either PHYS 13100 or 14100) based on performance on the mathematics or calculus placement test. Students concentrating in physics usually start their program with the honors sequence PHYS 14100-14200-14300; however, the PHYS 13100-13200-13300 sequence is an equally acceptable pathway to the degree.

Mathematics. The mathematics requirement is a calculus sequence (MATH 15100-15200-15300 or 16100-16200-16300) followed by Mathematical

Methods in Physics (MATH 22100). As an alternative to MATH 22100, students may substitute an Analysis sequence (MATH 20300-20400-20500 or 20700-20800-20900) though they will subsequently need to acquire certain math tools, as needed, on their own. However, students interested in pursuing further study in physics *and* mathematics are strongly encouraged to take both MATH 22100 and an Analysis sequence (the latter beginning either concurrent with or after MATH 22100).

For students starting their program with the PHYS 13100-13200-13300 sequence, MATH 15300/16300 should be replaced by MATH 22000. This course in mathematical methods introduces tools typically used in the PHYS 14100-14200-14300 sequence, and ensures that a student taking PHYS 13100-13200-13300 will possess the mathematical background needed for subsequent physics course work. (Note that *entering* students placing out of MATH 15100-15200 have the option of taking MATH 20000-20100-20200 in their first year. This will satisfy both the MATH 15300/16300/22000 and 22100 concentration requirements.)

Finally, all physics concentrators interested in taking applied math courses beyond MATH 22100 should consider MATH 27000, 27300, and 27500.

Summary of Requirements

General		PHYS 13100-13200 or 14100-14200†
Education		MATH 15100-15200† or 16100-16200
Concentration	1	PHYS 13300 or 14300†
	1	MATH 15300† or 16300 or 22000
	1	MATH 22100
	1	PHYS 15400
	1	PHYS 18500
	2	PHYS 23400-23500
	2	PHYS 22500, 22700
	1	PHYS 19700
	4	electives*
	14	

† *Credit may be granted by examination.*

Plus the following courses for honors candidates:

Option A		**Option B**	
3	PHYS 34100-34200-34300 or approved alternative graduate sequence	3	PHYS 29100-29200-29300

* Electives may be selected from the following menu:

- PHYS 23600, 23700, 22600, 25000, 25100, 25300, 26100, 26400
- ASTR 24100-24200
- MATH 20400-20500, 27000, 27300, 27500 (no more than two to be used as concentration electives)
- other courses approved by the concentration chair for physics

Elective notes: MATH 20400-20500 cannot be counted towards the concentration electives if 20300-20400-20500 is substituted for MATH 22100. Also, ASTR 24100-24200 cannot be counted towards the concentration electives if used to satisfy requirements for the specialization in astrophysics.

Sample Programs. The sample programs below illustrate different paths for fulfilling the physics concentration requirements. Concentration electives are indicated by an asterisk (*).

In the following example, the optional Analysis sequence partially satisfies concentration electives. The remaining electives are PHYS 23600 and 23700, which provide a particularly strong foundation for graduate study in physics. The optional PHYS 29100-29200-29300 sequence allows for completion of a bachelor's thesis.

First year	PHYS 14100-14200-14300 MATH 16100-16200-16300
Second year	PHYS 15400, 18500, 23400 MATH 22100, 20300-20400*
Third year	PHYS 23500, 22500, 22700 MATH 20500*
Fourth year	PHYS 19700, 23600*, 23700* (PHYS 29100-29200-29300)

The next example shows a PHYS 13100-13200-13300 pathway. Here, optional courses in applied mathematics are used as concentration electives, with other electives chosen to fit student interests and postgraduate plans.

First year	PHYS 13100-13200-13300 MATH 15100-15200, 22000
Second year	PHYS 15400, 18500, 23400 MATH 22100, 27300*, 27500*
Third year	PHYS 23500, 22500, 22700
Fourth year	PHYS 19700, elective*, elective* (PHYS 29100-29200-29300)

Note that the concentration requirements can also be completed in three years by "doubling up" on some of the nonelective courses. For example, PHYS 23500 and 19700 may be taken concurrently in the third year, and PHYS 22500, 22700 may be concurrent with 18500, 23400 in the second year. This provides more options in the third and fourth year for electives (as well as research or graduate course work).

The specialization in astrophysics might be pursued by taking ASTR 24100-24200, 28000/30500 in either the third or fourth year.

Finally, the sample programs shown here are only meant to be illustrative. Students are encouraged to speak with either of the Departmental Counselors in planning their individual programs, especially regarding the selection of electives.

Introductory Course. The introductory course in physics is divided into three variants so students may learn with others who have comparable physics and mathematics backgrounds, or similar interdisciplinary interests. The prerequisite for all three variants is a first-year calculus sequence: MATH 13100-13200-13300, 15100-15200-15300, or 16100-16200-16300. (NOTE: MATH 15100-15200-15300 or 16100-16200-16300 may be taken concurrently.) The essential physics content of these variants is the same. Both PHYS 13100-13200-13300 and 14100-14200-14300 prepare students for further courses in the Department of Physics.

Unless excused by satisfactory performance on the Advanced Placement physics test, first-year students are assigned to a variant of general physics based on the results of the calculus placement test. Transfer students who have satisfactorily completed calculus-based introductory physics courses at another university may be granted appropriate transfer credit upon petition to and approval by the concentration chair. However, the procedures for obtaining credit for the lab portions of the courses, described in the following section on Advanced Placement, applies. Third- and fourth-year students are assigned to a variant based on their GPA in previous mathematics and chemistry courses taken in the College. For entry into PHYS 13100, this GPA must be above 2.5; for entry into PHYS 14100, it must be above 3.0. A student who is unhappy with his or her level of introductory physics placement may submit a petition in writing to the undergraduate program chair (KPTC 205).

A student who completes PHYS 14100 or 14200 with a grade below *C* is normally required to move to PHYS 13200 or 13300 the following quarter. Petitions for waiver of this requirement must be presented to the undergraduate program chair before the second day of the succeeding course. A student who receives an *A* or *A*- in PHYS 13100 may petition the undergraduate program chair to move to PHYS 14200.

Advanced Placement. Students who took the C Advanced Placement examination in physics prior to matriculation in the College and received a grade of 4 or 5 are given credit for PHYS 12100-12200-12300.

The Department of Physics also administers accreditation examinations in PHYS 12100-12200-12300 and PHYS 14100-14200-14300 at the beginning of the corresponding quarter of each year. Students may receive credit for the lecture portion of one or more quarters of general physics on the basis of their performance on these examinations. All students who receive advanced standing on the basis of accreditation examinations are interviewed by the undergraduate program chair to determine the extent of their lab experience. Those who have not completed the equivalent of the lab portions of the courses are asked to do some or all of the experiments when the relevant courses are offered.

Grading. All regular (nonresearch) physics courses must be taken for quality grades. The Department of Physics requires students to pass General Physics I, II, and III and PHYS 15400, 18500, and 23400 with a GPA of 2.0 or higher to continue in the concentration program. To graduate with a concentration in physics, the College requires students to achieve a minimum GPA of 2.0 in the courses listed under "Concentration" in the preceding Summary of Requirements section. Any grade conferring course credit may be counted toward the minimum GPA requirements at the time of graduation. Incompletes are permitted only under exceptional circumstances.

Opportunities for Participation in Research. The physics program offers unique opportunities for College students to become involved actively in the research work being conducted by faculty and graduate students of the department. The focus of much of this undergraduate research is structured around the Bachelor's Thesis (PHYS 29100-29200-29300). Alternatively, third- or fourth-year students concentrating in physics may register for research for academic credit (PHYS 29700). There are other, more limited, openings for students at any level to become involved in research through regular part-time employment in a faculty member's lab or research group. Students concentrating in physics are encouraged to participate in research through one of these arrangements.

Honors Program. There are two routes to a B.A. honors degree. Both require a minimum GPA of 3.0 in the courses listed under "Concentration" in the preceding Summary of Requirements section. In the first route, the student must pass an approved sequence of three graduate courses to become eligible for a B.A. honors degree. Normally, the recommended 30000-level sequence is PHYS 34100-34200-34300; however, if approval is obtained from the concentration chair (KPTC 201), it may be replaced by another sequence of graduate courses in physics or graduate courses offered by the departments of astronomy, biophysics, chemistry, geophysical sciences, or mathematics. The second route to earning a B.A. honors degree is to register for PHYS 29100-29200-29300 (Bachelor's Thesis) and earn a grade of *B* or higher based on a bachelor's thesis describing an approved research project completed during the year.

Degree Program in Physics with Specialization in Astrophysics. The concentration program leading to a B.A. in physics with a specialization in astrophysics is a version of the B.A. in physics. The degree is in physics, with the designation "with specialization in astrophysics" included on the final transcript. Candidates are required to complete all requirements for the B.A. degree in physics, plus a two-quarter sequence in astrophysics (ASTR 24100-24200), plus either a third course in astrophysics (ASTR 28000 or ASTR 30500) or a senior thesis project in physics (PHYS 29100-29200-29300) on a topic in astrophysics. If the latter option is chosen, the thesis topic must be approved by the concentration chair. (This thesis may simultaneously fulfill part of the requirements for an Honors Degree in physics.) A grade of at least *C*- must be obtained in each course.

Faculty

I. D. Abella, E. C. Blucher, J. E. Carlstrom, S. M. Carroll, P. Cluzel, J. I. Collar, A. V. Crewe, J. W. Cronin, D. E. Eastman, P. G. O. Freund, H. J. Frisch, S. B. Gazes, R. P. Geroch, D. G. Grier, I. Gruzberg, P. Guyot-Sionnest, J. Harvey, R. H. Hildebrand, H. M. Jaeger, L. P. Kadanoff, W. Kang, K.-J. Kim, Y.-K. Kim, D. Kutasov, R. Levi-Setti, K. Levin, J. Lykken, E. J. Martinec, G. F. Mazenko, F. S. Merritt, S. Meyer, D. Müller, S. R. Nagel, Y. Nambu, J. J. O'Gallagher, R. Oehme, M. J. Oreglia, E. N. Parker, J. E. Pilcher, T. F. Rosenbaum, J. L. Rosner, R. Rosner, G. Savard, J. P. Schiffer, S. S. Sethi, M. J. Shochet, S. P. Swordy, M. Turner, C. E. M. Wagner, Y. W. Wah, R. M. Wald, P. Wiegmann, B. Winstein, R. Winston, T. A. Witten, W. W. Zhang

Courses: Physics (PHYS)

12100-12200-12300, 13100-13200-13300, and 14100-14200-14300. General Physics I, II, III. *PQ: For all three variants, a first-year calculus sequence (MATH 13100-13200-13300, 15100-15200-15300, or 16100-16200-16300) and appropriate placement recommendation. (NOTE: MATH 15100-15200-15300 or 16100-16200-16300 may be taken concurrently.) Calculus is used in all three sequences. Any of these sequences meets the general education requirement in physical sciences.* Although the essential physics content of these variants is similar, PHYS 13100-13200-13300 and 14100-14200-14300 prepare students for further courses in the Department of Physics, while PHYS 12100-12200-12300 includes a broader emphasis on interdisciplinary applications, such as in biology. Two sections of Variant B (PHYS 13100-13200-13300) are offered.

12100-12200-12300. General Physics I, II, III (Variant A). *PQ: Second-year standing.* This is a one-year sequence in the fundamentals of physics. Topics include classical mechanics, electricity and magnetism, wave motion, optics, and an introduction to modern physics. *Autumn, Winter, Spring. L.*

13100-13200-13300. General Physics I, II, III (Variant B). *PQ: More advanced mathematical abilities and training recommended.* This is a one-year sequence in the fundamentals of physics. Topics include classical mechanics, electricity and magnetism, wave motion, optics, and an introduction to modern physics. *Section a: Autumn, Winter, Spring. Section b: Autumn, Winter, Spring. L.*

14100-14200-14300. General Physics I, II, III (Honors). *PQ: Recommended to concentrators. Advanced knowledge of mathematics and good high school physics course helpful.* This is a one-year sequence in the fundamentals of physics. Topics include classical mechanics, electricity and magnetism, wave motion, and optics. Modern physics is also introduced. Multivariable and vector calculus is used. *Autumn, Winter, Spring. L.*

15400. Modern Physics. *PQ: PHYS 14300, or PHYS 13300 and MATH 22000.* Topics in this introduction to quantum physics include blackbody radiation, Einstein's quantum theory of light, the wave nature of particles, matter waves and wave-particle duality, atomic structure and energy levels, quantum mechanics and the Schrödinger equation, box quantization, barrier penetration and tunnelling, and the hydrogen atom. Applications to nuclear and solid-state physics are presented. *Autumn. L.*

18500. Intermediate Mechanics. *PQ: PHYS 13100 or 14100, and MATH 22100 or 20300.* Topics include a review of Newtonian mechanics, conservative forces, integrable problems, calculus of variations, Lagrangian and Hamiltonian mechanics, generalized coordinates, canonical momenta, phase space, and constrained systems. Additional topics are central-force motion, noninertial reference frames, and rigid-body motion. *Winter.*

19700. Statistical and Thermal Physics. *PQ: PHYS 23400, and MATH 22100 or 20500.* Elements of probability theory; statistical descriptions of physical systems, equilibrium and fluctuations, thermodynamics, canonical ensembles, the equipartition theorem, and kinetic theory are examined. *Autumn.*

22500, 22700. Intermediate Electricity and Magnetism I, II. *PQ: PHYS 13200 or 14200, and MATH 22100 or 20500.* Topics include electrostatics, magnetostatics, electromagnetic induction, electric and magnetic fields in matter, plane electromagnetic waves, reflection and refraction of electromagnetic waves, and electromagnetic radiation. *Winter, Spring.*

22600. Electronics. *PQ: PHYS 12200, 13200, or 14200; or equivalent.* The goal of this hands-on experimental course is to develop confidence, understanding, and design ability in modern electronics. This is *not* a course in the physics of semiconductors. In two lab sessions a week, students explore the properties of diodes, transistors, amplifiers, operational amplifiers, oscillators, field effect transistors, logic gates, digital circuits, analog-to-digital and digital-to-analog converters, phase-locked loops, and more. Lectures supplement the lab. *Spring. L.*

23400. Quantum Mechanics I. *PQ: PHYS 15400, and MATH 22100 or 20400.* A study of wave-particle duality leading to the basic postulates of quantum mechanics is presented. Topics include the uncertainty principle, applications of the Schrödinger equation in one and three dimensions, the quantum harmonic oscillator; and the hydrogen atom, rotational invariance and angular momentum, and spin. *Spring. L.*

23500. Quantum Mechanics II. *PQ: PHYS 23400.* A review of quantum mechanics is presented, with emphasis on Hilbert space, observables, and eigenstates. Topics include spin and angular momentum, time-independent perturbation theory, fine and hyperfine structure of hydrogen, the Zeeman and Stark effects, many-electron atoms, molecules, the Pauli exclusion principle, and radiative transitions. Additional topics are presented as time permits. *Autumn. L.*

23600. Solid State Physics. *PQ: PHYS 23500 and 19700.* Topics include crystal structure and crystal binding, Boltzmann, Bose-Einstein, and Fermi-Dirac statistics, lattice vibrations and phonons, liquid helium, the free-electron model of a metal, the nearly-free-electron model, semiconductors, and optical properties of solids. *Winter. L.*

23700. Nuclei and Elementary Particles. *PQ: PHYS 23500.* This class covers topics such as nuclear structure, processes of transformation, observables of the nucleus, passage of nuclear radiation through matter, accelerators and detectors, photons, leptons, mesons, and baryons, hadronic interactions, and the weak interaction. *Spring. L.*

25000. Computational Physics. *PQ: PHYS 13300 or 14300 required; knowledge of computer programming not required.* This course is an introduction to the use of computers in the physical sciences. After an introduction to programming basics, the following topics are covered: numerical solutions to fundamental types of problems; techniques for manipulating large data sets; computer simulations of complex systems. Additional topics may include an introduction to graphical programming, with applications to data acquisition and device control. *Winter. L.*

26400. Spacetime and Black Holes. *PQ: PHYS 185, and PHYS 227 or MATH 221 or consent of instructor.* This course is an introduction to general relativity. After a review of special relativity and four-dimensional spacetime, the basic tools of physics in a curved spacetime are introduced. The Schwarzschild solution describing both black holes and the exteriors of stars and planets are presented, and the behavior of objects in a Schwarzschild spacetime are extensively studied. The course concludes by introducing the dynamical equations relating energy and momentum to spacetime curvature (Einstein's equations). *Spring.*

29100-29200-29300. Bachelor's Thesis. *PQ: Open to concentrators with fourth-year standing and consent of instructor. Students are required to submit the College Reading and Research Course Form in Autumn Quarter. Students receive a grade in each quarter of registration:* P/F *grading in Autumn and Winter Quarters, and quality grading in Spring Quarter.* This yearlong sequence of courses is designed to involve the student in current research. Over the course of the year, the student works on a research project in physics or a closely related field (e.g., astrophysics) leading to the writing of a bachelor's thesis. A student who submits a satisfactory thesis, earns a grade of *B* or higher based on the project, and achieves a GPA of 3.0 or higher in the required undergraduate physics courses is awarded a B.A. with honors. The project may be one suggested by the instructor or one proposed by the student and approved by the instructor. Most work is done within the research groups of faculty members, but some experimental projects are done in the student project lab. In every case, all phases of the project (including the literature search, design and construction of the experiments, and analysis) must be done by the student. The instructor, faculty adviser, postdocs, and graduate students are, of course, available for consultation. *Autumn, Winter, Spring.*

29700. Participation in Research. *PQ: Consent of instructor and departmental counselor. Open to concentrators with third- or fourth-year standing. Students are required to submit the College Reading and Research Course Form. With consent of instructor, this course is available for either quality grades, or for* P/F *or* P/N *grades.* By mutual agreement, students work in a faculty member's research group. Participation in research may take the form of independent work, with some guidance, on a small project or of assistance in research to an advanced graduate student or research associate. A written report must be submitted at the end of the quarter. Students may register for PHYS 29700 for as many quarters as they wish; students need not remain with the same faculty member each quarter. *Summer, Autumn, Winter, Spring. L.*

31600. Advanced Classical Mechanics. *PQ: PHYS 18500.* This course begins with variational formulation of classical mechanics of point particles, including discussion of the principle of least action, Poisson brackets, and Hamilton-Jacobi theory. These concepts are generalized to continuous systems with infinite number of degrees of freedom, including a discussion of the transition to quantum mechanics. *Autumn.*

32200-32300. Advanced Electrodynamics I, II. *PQ: PHYS 22700 and 23500*. This two-quarter sequence in electromagnetism covers electromagnetic properties of continuous media, gauge transformations, electromagnetic waves, radiation, relativistic electrodynamics, Lorentz theory of electrons, and theoretical optics. There is considerable emphasis on the mathematical methods behind the development of the physics of these problems. *Winter, Spring.*

33000-33100. Mathematical Methods of Physics I, II. *PQ: PHYS 22700.* This is a two-quarter sequence providing essential background for electromagnetism and quantum mechanics. The Autumn Quarter covers differential equations, complex analysis, boundary value problems, and some special functions. The Winter Quarter includes Sturm-Liouville and eigenvalue problems, applications of functional analysis, Green's functions, path integrals, variational methods, singularities of differential equations, more special functions, and elementary group theory. *Autumn, Winter.*

34100-34200-34300. Quantum Mechanics I, II, III. *PQ: PHYS 23500 and MATH 27300.* This three-quarter sequence covers wave functions and their physical content, one-dimensional systems, WKB method, operators and matrix mechanics, angular momentum and spin, two- and three-dimensional systems, the Pauli principle, perturbation theory, Born approximation, scattering theory, the Dirac equation, elementary quantum field theory, and Feynman path integrals. *Autumn, Winter, Spring.*

35200. Statistical Mechanics. *PQ: PHYS 19700 and 34100.* This course covers principles of statistical mechanics and their applications to physics and chemistry. *Spring.*