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 BA in physics includes a strong emphasis on 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).

Students who are majoring in other fields of study may also complete a minor in physics. Information follows the description of the major.

Program Requirements

Courses. The curriculum leading to the BA 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 physics electives that allow students to pursue specific interests. Students intending to pursue graduate work in astrophysics should consider the program leading to a BA in physics with a specialization in astrophysics, which is described later.

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

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 majoring 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 (PHYS 22100). As an alternative to PHYS 22100, students taking an Analysis sequence (MATH 20300-20400-20500 or 20700-20800-20900) may substitute MATH 20500 or 20900 for PHYS 22100, 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 should consider taking both PHYS 22100 and an Analysis sequence.

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 15300-20000-20100 in their first year. This will satisfy the mathematics requirements for the major (with MATH 20100 substituting for PHYS 22100).

Finally, entering students placing into MATH 13100 should consult the undergraduate program chair to plan a program of study.

Summary of Requirements

General Education	PHYS 13100-13200 or 14100-14200*; MATH 15100-15200* or 16100-16200	
Major	1	PHYS 13300 or 14300*
	1	MATH 15300* or 16300 or 22000
	1	PHYS 22100 or MATH 20500 or 20900
	1	PHYS 15400
	1	PHYS 18500
	2	PHYS 23400-23500
	1	PHYS 21100
	2	PHYS 22500, 22700
	1	PHYS 19700
	3	electives
	14	

** Credit may be granted by examination.*

Electives. In addition to specified course work, the physics major requires three electives. These electives may be selected from the following courses:

- all 20000-level physics courses except Bachelor's Thesis (PHYS 29100-29200-29300) and Participation in Research (PHYS 29700)
- ASTR 24100†, 24200†; BIOS 29326; CHEM 26300, 26800; GEOS 21200, 23200
- MATH 20400-20500‡ or 20800-20900‡, 27000, 27200, 27300, 27400, 27500 (no more than two to be used as program electives)
- other courses approved by the program chair for physics

† *Cannot be counted toward electives if used to satisfy requirements for the specialization in astrophysics.*
‡ *Neither MATH 20500 nor 20900 can be counted toward electives if substituted for PHYS 22100.*

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

In the following example, an Analysis sequence partially satisfies the physics elective requirements, while preserving the option of a second major in math. (If Analysis *replaces* PHYS 22100, then an additional elective must be taken.) 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 PHYS 22100, MATH 20300-20400*
Third Year	PHYS 21100 for three quarters (100 units total) PHYS 23500, 22500, 22700 MATH 20500*
Fourth Year	PHYS 19700, elective* (Optional thesis; PHYS 29100-29200-29300)

The next example shows a PHYS 13100-13200-13300 pathway. Here, the required MATH 22000 course replaces the third quarter of calculus, while optional courses in applied mathematics partially satisfy the elective requirements.

First Year	PHYS 13100-13200-13300 MATH 15100-15200, 22000
Second Year	PHYS 15400, 18500, 23400 PHYS 22100, MATH 27300*, MATH 27500*
Third Year	PHYS 21100 for three quarters (100 units total) PHYS 23500, 22500, 22700
Fourth Year	PHYS 19700, elective* (Optional thesis; PHYS 29100-29200-29300)

The required course in Experimental Physics (PHYS 21100) is a yearlong course. One quarter's credit (100 units) is granted in Spring Quarter after successful completion of the year's work. It is recommended, but not required, that this course be taken in the third year, concurrent with PHYS 23500.

Progress through the physics program can be accelerated 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). Note that it is possible to complete all program requirements in three years.

The specialization in astrophysics might be pursued by taking ASTR 24100-24200, 28200/30500 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 the departmental counselors in planning individual programs, especially regarding selection of mathematics courses and program 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.

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 program chair. However, the procedures for obtaining credit for the lab portions of the courses, described in the following section on Accreditation, 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 physics C Advanced Placement examinations prior to matriculation in the College may receive credit for some or all of PHYS 12100-12200-12300. Consult the section on Advanced Placement Credit elsewhere in this catalog for more information.

Accreditation. Accreditation examinations are administered for the content of PHYS 12100-12200-12300 and 14100-14200-14300. The first examination may be taken by incoming students *only* at the time of matriculation in the College. Students who pass the first examination (for PHYS 12100 or 14100) will receive credit for the lecture part of the course only and will then be invited to try the next examination of the series. All students who receive advanced standing on the basis of a physics accreditation examinations are interviewed by the undergraduate program chair to determine the extent of their lab experience. Additional laboratory work may be required.

Grading. All regular (nonresearch) physics courses must be taken for quality grading. The Department of Physics requires students to pass General Physics I, II, and III and PHYS 15400, 18500, and 23400 with an average of 2.0 or higher to continue in the program. Incompletes are permitted only under exceptional circumstances.

Opportunities for Participation in Research. The physics program offers unique opportunities for College students to become actively involved in the research being conducted by faculty of the department. Interested students are welcome to consult with the departmental counselors. The focus of much of the undergraduate research is structured around the Bachelor's Thesis (PHYS 29100-29200-29300). Alternatively, third- or fourth-year students majoring in physics may register for research for academic credit (PHYS 29700). In addition to these formal arrangements, students at any level may become involved in research by working in a faculty member's lab or research group on an extracurricular basis.

Honors. There are two routes to receiving a BA with honors. Both require a minimum GPA of 3.0 in the courses listed under Major in the preceding Summary of Requirements section. In the first route, the student must first pass an approved sequence of three graduate courses. The recommended 30000-level sequence typically is PHYS 34100-34200-35200; however, if approval is obtained from the program chair, this sequence may be replaced by another sequence of graduate courses. The second route to receiving a BA with honors 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 program leading to a BA in physics with a specialization in astrophysics is a version of the BA 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 BA degree in physics, plus a two-quarter sequence in astrophysics (ASTR 24100-24200), plus either a third course in astrophysics (ASTR 28200 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 program chair. (This thesis may simultaneously fulfill part of the requirements for honors in physics.) A grade of at least *C-* must be obtained in each course.

Minor Program in Physics

The minor in physics is designed to present a coherent program of study to students with a strong interest in physics but insufficient time to pursue the major. The courses required for the minor are: PHYS 13300/14300, 15400, 18500, 22100, and 23400; MATH 15300/16300/22000; and two electives. At least one of these electives must be either PHYS 19700 or 22500 or 23500, while the other elective may be any course that is required by the major or can be used as an elective for the major. The mathematics requirement for the minor is identical to the requirement for the major; please consult the description of the major for more information, particularly regarding MATH 22000 and PHYS 22100. Note that MATH 22000 and PHYS 22100 may be replaced by equivalent courses, as approved by the undergraduate program chair. Note also that the PHYS 13300/14300, PHYS 22100, and MATH 15300/16300/22000 requirements will be waived for those who must take these courses to satisfy the requirements of a major or another minor. Consequently, the number of additional courses needed for the minor will vary between five and eight.

Students who elect the minor program in physics must meet with the physics undergraduate program chair before the end of Spring Quarter of their third year to declare their intention to complete the minor. The approval of the program chair for the minor program should be submitted to a student's College adviser by the deadline above on a form obtained from the College adviser. Courses for the minor are chosen in consultation with the program chair.

Courses in the minor (1) may not be double counted with the student's major(s) or with other minors and (2) may not be counted toward general education requirements. Courses in the minor must be taken for quality grades, and students must have a GPA of 2.0 or higher in the minor. More than half of the requirements for the minor must be met by registering for courses bearing University of Chicago course numbers.

Faculty

I. D. Abella, D. Biron, E. C. Blucher, F. Canelli, M. Carena, J. E. Carlstrom, C. Chin, J. I. Collar, J. W. Cronin, D. E. Eastman, P. G. O. Freund, H. J. Frisch, M. L. Gardel, S. B. Gazes, R. P. Geroch, I. Gruzberg, P. Guyot-Sionnest, J. Harvey, R. H. Hildebrand, R. J. Hill, E. D. Isaacs, H. M. Jaeger, L. P. Kadanoff, W. Kang, K.-J. Kim, Y.-K. Kim, D. Kutasov, R. Levi-Setti, K. Levin, Z.-T. Lu, E. J. Martinec, G. F. Mazenko, F. S. Merritt, S. Meyer, D. Müller, S. R. Nagel, Y. Nambu, R. Oehme, M. J. Oreglia, E. N. Parker, J. E. Pilcher, D. D. Reid, T. F. Rosenbaum, J. L. Rosner, R. Rosner, R. Santra, G. Savard, J. P. Schiffer, S. S. Sethi, M. J. Shochet, S. P. Swordy, M. S. Turner, C. E. M. Wagner, Y. W. Wah, S. Wakely, R. M. Wald, P. Wiegmann, B. Winstein, 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. The first two courses of any sequence meet 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, fluids, electricity and magnetism, wave motion, optics, and modern physics. *Autumn, Winter, Spring. L.*

13100-13200-13300. General Physics I, II, III (Variant B). *Advanced knowledge of mathematics recommended.* This is a one-year sequence in the fundamentals of physics. Topics include classical mechanics, special relativity, electricity and magnetism, wave motion, optics, and heat. *Autumn, Winter, Spring. L.*

14100-14200-14300. General Physics I, II, III (Honors). *Advanced knowledge of mathematics and good high school physics course helpful. This course is recommended for students who are majoring in Physics.* This is a one-year sequence in the fundamentals of physics. Topics include classical mechanics, special relativity, electricity and magnetism, wave motion, optics, and heat. Multivariable and vector calculus is used. *Autumn, Winter, Spring. L.*

15400. Modern Physics. *PQ: PHYS 14300, or PHYS 13300 and MATH 22000.* This course is an introduction to quantum physics. Topics include Einstein's quantum theory of light, the wave nature of particles, atomic structure, the Schrödinger equation, quantum mechanics in one and three dimensions, barrier penetration and tunneling, and the hydrogen atom. Applications to nuclear and solid-state physics are presented. *Autumn. L.*

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

19700. Statistical and Thermal Physics. *PQ: PHYS 23400, and PHYS 22100 or MATH 20500.* This course develops a statistical description of physical systems. Topics include elements of probability theory, equilibrium and fluctuations, thermodynamics, canonical ensembles, the equipartition theorem, quantum statistics of ideal gases, and kinetic theory. *Autumn.*

21100. Experimental Physics. *PQ: PHYS 23400. Open only to students who are majoring in Physics. Credit is granted in Spring Quarter after successful completion of the year's work.* This is a yearlong laboratory course, offering experiments in atomic, molecular, solid-state, nuclear, and particle physics. As needed, additional material is presented in supplemental lectures. Content varies from quarter to quarter. *Autumn, Winter, Spring. L.*

22100. Mathematical Methods in Physics. *PQ: PHYS 14300, or PHYS 13300 and MATH 22000.* Topics include linear algebra and tensor analysis, ordinary and partial differential equations, calculus of variations, special functions, series solutions of differential equations, and integral transforms. *Autumn.*

22300. Topics in Mathematical Physics. *PQ: PHYS 18500; MATH 20500 or 20900.* This course covers selected topics in mathematical physics. Possible topics include differential geometry, group theory, Hilbert spaces, functional analysis, and topology. *Winter.*

22500, 22700. Intermediate Electricity and Magnetism I, II. *PQ: PHYS 13200 or 14200, and PHYS 22100 or MATH 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 or 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, we 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 PHYS 22100 or MATH 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, rotational invariance and angular momentum, the hydrogen atom, and spin. *Spring.*

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. *Autumn.*

23600. Solid State Physics. *PQ: PHYS 23500 and 19700.* Topics include a review of quantum statistics, crystal structure and crystal binding, lattice vibrations and phonons, liquid helium, the free-electron model of metals, the nearly-free-electron model, semi-conductors, and optical properties of solids. *Spring.*

23700. Nuclei and Elementary Particles. *PQ: PHYS 23500.* This course 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. *Winter.*

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

25500. Biological Physics. *PQ: PHYS 19700 or CHEM 26200.* This course is an introduction to the physics of living matter. Its goal is to understand the design principles from physics that characterize the condensed and organized matter of living systems. Topics include: basic structures of proteins, nucleotides, and biological membranes; application of statistical mechanics to diffusion and transport; hydrodynamics of low Reynolds number fluids; thermodynamics and chemical equilibrium; physical chemistry of binding affinity and kinetics; solution electrostatics and depletion effect; biopolymer mechanics; cellular mechanics and motions; and molecular motors. *Spring.*

26400. Spacetime and Black Holes. *PQ: PHYS 18500, and PHYS 22100 or MATH 20400 or consent of instructor.* This course introduces 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 is presented, and the behavior of objects in a Schwarzschild spacetime is extensively studied. The course concludes by introducing the dynamical equations relating energy and momentum to spacetime curvature (Einstein's equations). *Autumn.*

27100. Introduction to Cosmological Physics. *PQ: PHYS 18500 and 23500; PHYS 19700 recommended.* This course provides the observational basis for what

we know about the Universe: that it is expanding and that the rate of expansion is increasing, that the light elements were made during the first few minutes, that an unknown sector ("dark matter") is responsible for holding galaxies together, and that its energy density is dominated by a completely unknown component ("dark energy"). We develop the evidence for the widely accepted paradigm for the very early Universe: the inflationary scenario. Means of experimentally probing inflation and possible alternatives are also discussed. The mechanism for how the rich structure (galaxies) of the Universe arose from a relatively smooth beginning is developed. The role of the cosmic microwave background radiation in providing us cosmological information is emphasized. *Winter.*

28000. Current Research Topics in Physics. *PQ: PHYS 23500.* This course covers several research topics of current interest in physics. Topics chosen by the instructors may include neutrino masses, the quantum Hall effect, dark matter and dark energy, the physics of grains and glasses, the search for supersymmetry, and nanophysics, as well as others. The course is intended to acquaint students with forefront research in physics and to show how ideas from different areas of physics are combined in dealing with real-world problems. *Spring.*

29100-29200-29300. Bachelor's Thesis. *PQ: Open to students who are majoring in Physics 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 a quality grade 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 eligible to receive a BA with honors. The project may be one suggested by the instructor or one proposed by the student and approved by the instructor. In either 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, the faculty adviser, post-docs, 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 students who are majoring in Physics with third- or fourth-year standing. Students are required to submit the College Reading and Research Course Form. May be taken for* P/F *grading with consent of instructor.* 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 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. Mathematical Methods of Physics. *PQ: PHYS 22700.* Topics include complex analysis, linear algebra, differential equations, boundary value problems, and special functions. *Autumn.*

34100-34200. Advanced Quantum Mechanics I, II. *PQ: PHYS 23500, and PHYS 22100 or MATH 27300.* This two-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, and scattering theory. *Autumn, Winter.*

35200. Statistical Mechanics. *PQ: PHYS 19700 and 23500.* This course covers principles of statistical mechanics and thermodynamics, as well as their applications to problems in physics and chemistry. *Spring.*