PHYSICS

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Chair: Steve Chu
Associate Chair: Douglas D. Osheroff
Directors of Graduate Study: Alexander L. Fetter, Roger W. Romani
Director of Undergraduate Study: Douglas D. Osheroff
Professors: Patricia Burchat, Blas Cabrera, Steven Chu, Savas G. Dimopoulos, Sebastian Doniach, Alexander L. Fetter, Renata E. Kallosh, Aharon Kapitulnik, Robert B. Laughlin, Andrei D. Linde, Peter F. Michelson, Douglas D. Osheroff, Vahé Petrosian, H. Alan Schwettman, Zhi-Xun Shen, Stephen Shenker, Leonard Susskind, Robert V. Wagoner, Arthur B. C. Walker II, Stanley G. Wojcicki, Shoucheng Zhang
Associate Professors: Giorgio Gratta, Shamit Kachru, Roger W. Romani
Assistant Professors: Sarah Church, Hari Manoharan, Scott Thomas, Vladan Vuletic
Professors (Research): John A. Lipa, Phillip H. Scherrer, Todd I. Smith
Courtesy Professors: Richard Taylor, Richard N. Zare
Courtesy Assistant Professor: Eva Silverstein
Lecturer: Richard L. Pam
Consulting Professors: Gerald Fisher, Theodor Hansch
Consulting Associate Professor: Alex Silbergleit
Consulting Assistant Professor: Hal Edwards

The Russell H. Varian Laboratory of Physics, the nearby W. W. Hansen Experimental Physics Laboratory (HEPL), and the E. L. Ginzton Laboratory form a closely related complex which houses a range of physics activities from general courses through advanced research. At the Stanford Free Electron Laser Center, located in HEPL, tunable picosecond optical beams are available for materials and biomedical research at wavelengths that extend from the visible to the far infrared. Separate from this group is the Stanford Linear Accelerator Center (SLAC), a high energy physics lab which has as its principal tools a two-mile-long 50-GeV electron accelerator and a 6-GeV electron-positron storage ring. Also at SLAC are a 30 GeV electron-positron storage ring (PEP) and the Stanford Synchrotron Radiation Laboratory (SSRL). A high-energy facility, the Stanford Linear Collider (SLC), provides electron-positron collisions at about 100 GeV in the center of mass.

Professor Byer is director of HEPL, and Professors Cabrera, Lipa, Michelson, Scherrer, Schwettman, Smith, and Turneaure are members of the laboratory. The Ginzton Laboratory, HEPL, SLAC, and SSRL are listed in the "Independent Research Laboratories, Centers, and Institutes" section of this bulletin.

Stanford is a member of the Hobby-Eberly Telescope Consortium. This 10.4 meter telescope has begun operation at McDonald Observatory in Texas. There are opportunities for graduate and undergraduate students doing research projects to use this telescope.

Stanford has also built (with CalTech) an underground laboratory for the study of neutrino oscillations near the Palo Verde Nuclear Electric Power Generating Station, 50 miles west of Phoenix, Arizona. It is in operation and students are engaged in the construction and operation of the experiment.

The Physics Library, a center for the reading and study of physics and astronomy at all levels, includes current subscriptions and back sets of important journals together with textbooks, scholarly treatises in English, French, German, and Russian, and the collected works of the most eminent physicists.

Course work is designed to provide students with a sound foundation in both classical and modern physics. Students who wish to specialize in astronomy, astrophysics, or space science should consult the "Astronomy Course Program" section of this bulletin.

Three introductory series of courses include labs in which undergraduates carry out individual experiments. The Intermediate and Advanced Physics Laboratories offer facilities for increasingly complex individual work. Undergraduates are also encouraged to participate in research; most can do this through the honors program.

Graduate students find opportunities for research in the fields of astrophysics, atomic physics/laser science, coherent optical radiation, condensed matter physics, high energy physics, intermediate energy physics, low temperature physics, and theoretical physics. Opportunities for research are also available with the faculty at SLAC in the areas of theoretical and experimental particle physics and accelerator design, and with the faculty in Physics and Applied Physics in the areas of astrophysics, materials research, novel imaging technology, photon science, quantum electronics, and theoretical and experimental condensed matter physics.

The number of graduate students admitted to the Department of Physics is strictly limited. Students should submit applications by January 1 for the following Autumn Quarter. Graduate students may normally enter the department only at the beginning of Autumn Quarter.

UNDERGRADUATE PROGRAMS

The study of physics is undertaken by three principal classes of undergraduates: those including physics as part of a general education; those preparing for careers in professional fields that require a knowledge of physics, such as medicine or engineering; and those preparing for teaching or research careers in physics or related fields. Physics courses numbered below 200 are planned to serve all three of these groups. The courses numbered above 200 meet the needs mainly of the third group, but also of some students majoring in other branches of science and in engineering.

BACHELOR OF SCIENCE

Requirements for the degree of Bachelor of Science in Physics are: Physics 61, 63, 64, 65, 66, 70, 105, 106, 107, 110, 111, 120, 121, 122, 130, 131, 132, 170, 171, 201; Mathematics 51, 52, 53, 131; any one additional math course numbered 100 or higher; and one of the following advanced physics courses: 135, 160, 161, 172, 181, 203, 204 or 262. (The Physics 40 series can replace the 60 series requirements, and Mathematics 51H, 52H, and 53H may substitute for Mathematics 51, 52, and 53.) The department advises the study of some chemistry, for example, Chemistry 31 or 32, 33, and 35 and some computer science, for example, CS 106. Mathematics and physics courses taken to satisfy the department's major requirements cannot be taken on a credit/no credit basis. Prospective physics majors are also recommended to take Physics 59, Current Research Topics.

In an effort to increase the flexibility of the Physics major for students with strong interests in allied disciplines such as biology, chemistry, computer science, electrical engineering, earth sciences, or mathematics, selected courses from the Physics major (indicated by an * below) may be replaced with a concentration of correspondingly advanced courses in one of these other fields. In all cases, these modifications to the Physics major towards an interdisciplinary course of study should be worked out beforehand with the student's adviser and must be documented with the undergraduate program coordinator.

To decide which introductory sequence is appropriate, students contemplating majoring in physics are urged to consult with the instructor of Physics 61 or Physics 41, or the undergraduate program coordinator, at the earliest possible date to see which sequence is the most suitable. Students who begin taking an entry level physics course after their freshman year and wish to major in physics are generally advised to take the Physics 61, 63, 65 sequence, provided they have previously taken Mathematics 41.

Undergraduates are offered help with physics problems in the department tutoring center, the Reference Frame, which is staffed Monday through Thursday.

REQUIRED COURSES FOR MAJORS

INTRODUCTORY SEQUENCE

Course No. and Subject	*Qtr. and Units*	
Physics 41. Mechanics	A	3
Physics 43. Electricity	W	3
Physics 45. Magnetism	S	3
Physics 46. Electricity and Magnetism Lab	S	1

Physics 47. Light and Heat	A	4
Physics 48. Light and Heat Lab	A	1
or		
Physics 61. Mechanics	A	4
Physics 63. Electricity and Magnetism	W	4
Physics 64. Electricity and Magnetism Lab	W	1
Physics 65. Optics and Thermodynamics	S	4
Physics 66. Optics and Thermodynamics Lab	S	1
and		
Math. 51, 52, 53. Multivariable Mathematics (*or* H series)	A,W,S	15
Physics 59. Current Research Topics (recommended)	W	1

INTERMEDIATE SEQUENCE

Physics 70. Modern Physics	A	3
Physics 105,106,107. Intermediate Laboratory	A,W,S	9
Physics 110,111. Intermediate Mechanics	W,S	8
Physics 120,121,122*. Intermediate Electricity and Magnetism	A,W,S	12
and		
Math. 131. Partial Differential Equations	W,S	3

ADVANCED SEQUENCE

Physics 130,131,132*. Quantum Mechanics	A,W,S	12
Physics 170,171. Statistical Mechanics	A,W	8
Physics 201*. Advanced Physics Laboratory	A,S	3
one advanced Physics elective*:		
Physics 135. Computational Physics	A	3
Physics 160,161. Astrophysics	A,S	6
Physics 172. Solid State Physics	S	3
Physics 181. Modern Optics	A	3
Physics 203. Advanced Physics Laboratory	A,S	3
Physics 204. Theoretical Physics	A	3
Physics 262. Gravitation and Astrophysics	S	3
and		
one advanced Mathematics elective (100 level or higher)		

* These courses may be replaced with a concentration of correspondingly advanced courses in another field as part of an interdisciplinary program. This must be discussed with the student's adviser and documented with the undergraduate program coordinator.

CONCENTRATION IN ASTROPHYSICS

This area encompasses the study of the universe and its constituent planets, stars, and galaxies. The courses recommended for a concentration in astrophysics are four undergraduate courses; one laboratory course, 100; and three lecture courses: Electrical Engineering 106 (see also the Astronomy Program) on planetary exploration; Physics 160 on stars and galactic structure; and Physics 161 on galaxies and cosmology. More advanced students, and in particular, those undergraduates whose honors thesis topic is in this concentration area, are strongly urged to take the two introductory graduate courses on Astrophysics and Gravitation, 260 and 262.

MINORS

C0NCENTRATIONS IN PHYSICS

The minor declaration deadline is three quarters before graduation (that is, beginning Autumn Quarter if the student is graduating at the end of Spring Quarter). All courses for the minor must be taken at Stanford University, and a letter grade of 'C' or better must be received for all units applied toward the minor, (with the exception of Physics 105, 106, and 107 which may be taken for CR/NC).

An undergraduate minor in Physics requires the following course work:

Non-Technical—For students whose majors do not require the Physics 40 or 60 series:

Course No.	*Units*
Physics 41, 43, 45, 47 (choose three out of four)	9-10
Physics 25 or 70 (70 is technically much more demanding)	3
Choose two lab courses from the following:	
Physics 46, 48, 72	2
Choose two courses from the following:	
Physics 100, 105, 106, 107, 110, 111*, 120*, 121*, 130*, 131*, 160, 161, 170*, 171*	6-8
Total	20-23

Technical—For students whose majors require the Physics 40 or 60 series:

Physics 70, 72	4
Physics 110, 120*, 130*, 170*	16
Choose two courses from the following:	
Physics 105, 106, 107, 111*, 121*, 122*, 131*, 132*, 160, 161, 171*, 172*	6-8
Total	24-28

* Requires differential equations.

CONCENTRATIONS IN ASTRONOMY

Modern astronomy deals with the origin and evolution of the dramatic range of objects observed in our Universe. The language of this study is physics. Those wishing to pursue advanced work in astrophysics or related fields should major in physics with an astrophysics concentration. The minor programs below are designed primarily for those from other disciplines with a general interest in astronomy. In particular, the non-technical minor treats the subject in a more descriptive manner.

To be accepted to the minor program, students need to obtain an adviser selected from the faculty in the Astronomy Course Program. The minor declaration deadline is three quarters before graduation (that is, beginning Autumn Quarter if the student is graduating at the end of Spring Quarter). All courses for the minor must be taken at Stanford University, and a letter grade of 'C' or better must be received for all units applied toward the minor.

An undergraduate minor in Astronomy requires the following course work:

Non-Technical—For students whose majors do not require the Physics 40 series:

Course No.	*Units*
Physics 21, 23, 25	9
Physics 50 or 100	3-4
Choose two courses from the following:	
Physics 15, 16, 18N, 27, 162*	6-7

Technical—For students whose majors require the Physics 40 series:

Physics 27*	3
Physics 70	3
Physics 100	4
Physics 160*, 161*, 162*	9
Total	18-20

* With approval of the minor adviser and the chair of the Astronomy program, 3 units of Physics 169 (Independent Study in Astrophysics) may be substituted for one of these courses. This independent study can either be constituted as a directed reading program or participation in a research project.

HONORS PROGRAM

The department offers a program leading to the degree of Bachelor of Science in Physics with Honors as follows:

1. Students must submit an Honors Program Proposal to the Undergraduate Program Coordinator once they find a physics project, either theoretical or experimental, in consultation with individual faculty members. Proposal forms are available from the Physics Undergraduate Center and must be submitted by November 1 of the year in which the students' degree will be conferred.
2. Credit for the project is assigned by the adviser within the framework of Physics 205 or Astronomy 169. The work done in the honors program may not be used as a substitute for regularly required courses.
3. Both a written report and a presentation of the work at its completion is required for honors. By mid-May, each honors candidate is required to present his or her project at the department's Honors Presentations. (This event is publicized and is open to the general public. The expectation is that the student's adviser and second reader, along with all other honors candidates, will attend.)
4. The decision as to whether a given independent study project does or does not merit award of honors is made jointly by the student's honors adviser and the second reader for the written thesis. This decision is based on the quality of both the honors work and the other work in physics.

GRADUATE PROGRAMS

MASTER OF SCIENCE

The department does not offer a coterminal degree program, nor a separate program for the M.S. degree, but this degree may be awarded for a portion of the Ph.D. degree work.

University requirements for the master's degree, discussed in the "Graduate Degrees" section of this bulletin, include registration for at least three quarters at full tuition as a graduate student and completion of 36 units of course work after the bachelor's degree. Among the department requirements are a grade point average (GPA) of at least 'B' in courses 201, 203, 210, 211, 212, 220, 221, 230, 231, 232, or their equivalents. Up to 6 of these required units may be waived on petition if a thesis is submitted.

DOCTOR OF PHILOSOPHY

The University's basic requirements for the Ph.D. are discussed in the "Graduate Degrees" section of this bulletin. The minimum department requirements for the Ph.D. degree in Physics consist of completing all courses listed below, and at least one quarter from each of two subject areas (among condensed matter, quantum optics and atomic physics, astrophysics and gravitation, and nuclear and particle physics) chosen from courses with numbers above 232, except 290 and 294. The requirements in this list may be fulfilled by passing the course at Stanford or passing an equivalent course elsewhere: 201, 203, 210, 211, 212, 220, 221, 230, 231, 232, 290, 294. A grade point average (GPA) of at least 'B' is required in all the courses taken toward the degree.

All Ph.D. candidates must have math proficiency equivalent to the following Stanford math courses: 106, 113, 114, 130, 131, 132.

Prior to making an application for candidacy, each student is required to pass a comprehensive qualifying examination on undergraduate physics. This exam is given annually at the beginning of Winter Quarter. Graduate physics is tested by the exams in the first-year courses (210-232). A thesis proposal must be submitted during the third year. In order to assess the direction and progress toward a thesis, an oral report and evaluation is required during the fourth year. After completion of the dissertation, each student must take the University oral examination (defense of dissertation). The Physics faculty also believe that a scientist should have facility with a foreign language for cultural reasons as well as to establish better contact at meetings in foreign countries.

Three quarters of teaching (including a demonstrated ability to teach) are a requirement for obtaining the Ph.D. in Physics.

Students interested in applied physics and biophysics research should also take note of the Ph.D. granted independently by the Department of Applied Physics and by the Biophysics Program administered through the Department of Chemistry. Students interested in astronomy, astrophysics, or space science should also consult the "Astronomy Course Program" section of this bulletin.

Ph.D. MINOR

Minors in Physics must take at least six courses numbered 210 to 232 among the 20 required units. All prospective minors must obtain approval of their physics course program from the Physics Graduate Study Committee at least one year before award of the Ph.D.

FELLOWSHIPS AND ASSISTANTSHIPS

The Department of Physics makes an effort to support all its graduate students through fellowships, teaching assistantships, research assistantships, or a combination of sources. Information on application procedures is mailed with the admission information.

TEACHING CREDENTIALS

For information on teaching credentials, consult the "School of Education" section of this bulletin or address an inquiry to the Credential Administrator, School of Education.

The degree of Master of Arts in Teaching is offered jointly by this department and the School of Education. The degree is intended for those who have a teaching credential and wish to strengthen their academic preparation. The program consists of a minimum of 25 units in the teaching field and 12 units in the School of Education. A suggested minimum would be Physics 64, 66, 70, 105, 110, 111, 120, 121; and Mathematics 130, 131. Detailed requirements for the degree are outlined in the "School of Education" section of this bulletin.

COURSES

There are four series of beginning courses. One course from the teen series (11, 15, 16, 19, 27) is recommended for the humanitites or social science student who wishes to become familiar with the methodology and content of modern physics. The Twenty Series (21, 22, 23, 24, 25, 26) is recommended for general students and for students preparing for medicine or biology. The Forty Series (41, 43, 45, 46, 47, 48) is for students of engineering chemistry, geology, mathematics, or physics. The Advanced Freshman Series (61, 63, 64, 65, 66) is for the well-prepared student and is the preferred introductory series for those physics majors who have the appropriate background.

Both the Twenty and Forty Series consist of demonstration lectures on the fundamental principles of physics, problem work on application of these principles to actual cases, and lab experiments correlated to the lectures. Their objectives are not only to give information on particular subjects, but also to provide training in the use of the scientific method. The primary difference between the two series of courses is that topics are discussed more thoroughly and treated with greater mathematical rigor in the Forty Series.

Courses beyond 99 are numbered in accordance with a three-digit code. The first digit indicates the approximate level of the course: undergraduate courses (1); first-year graduate courses (2); more advanced courses (3); research, special, or current topics (4). The second digit indicates the general subject matter: laboratory (0); general courses (1), (2), (3); nuclear physics (4); elementary particle physics (5); astrophysics, cosmology, gravitation (6); condensed matter physics (7); optics and atomic physics (8); miscellaneous courses (9).

UNDERGRADUATE

(WIM) indicates that the course meets the Writing in the Major requirements.

ASTRONOMY

For further information on astronomy and astrophysics courses, consult the Astronomy Course Program.

15,16. Topics in Modern Astronomy—15 and 16 are for students not majoring in the physical sciences and are taught in different quarters by different instructors. They are related in topic but emphasize different aspects of modern astronomy and cosmology. Students may take 15, 16 individually or in sequence.

15. The Nature of the Universe—Introduction to the structure, origin, and evolution of the major components of the Universe: planets, stars, and galaxies. Emphasis is on the formation of the Sun and planets, the evolution of stars, and the structure and content of our galaxy. Topics: cosmic enigmas (dark matter, black holes, pulsars, X-ray sources), star birth and death, and the origins of and search for life in our solar system and beyond. GER:2a (DR:5)

3 units, Aut (Cabrera)

16. Cosmic Horizons—Introduction to the origin and evolution of our universe and its contents: stars, galaxies, quasars, etc. The overall structure of the cosmos and the physical laws that govern matter, space, and time. Topics: the evolution of the cosmos from its primeval fireball, the origin of the elements and the formation of stars and galaxies, exotic astronomical objects (black holes, quasars, supernovae, and gamma ray bursts), dark matter, and the fate of the cosmos.

3 units, Win (Linde)

18N. Stanford Introductory Seminar: Revolutions in Concepts of the Cosmos—Preference to freshmen. Faculty led dialogue. Introduction to four revolutionary changes in humanity's concept of the cosmos (explored at the Stanford Observatory): Copernicus' heliocentric model of the solar system, Herschel's concept of the galaxy as a collection of stars, Shapley's model of the Milky Way galaxy, and Hubble's dicovery that the universe is expanding. Enrollment limited to 20 in one section. GER:2a (DR:5)

4 units, Spr (Staff)

27. Evolution of the Cosmos—Similar to 15 or 16 but at a somewhat more quantitative level. The origin and evolution of astronomical objects: planets, stars, black holes, galaxies, and the universe at large; emphasizing modern developments in astronomy and physics relevant to the subject matter. The development of life in the universe. (Algebra is used.) Offered occasionally. Recommended: high school physics and calculus. GER:2a (DR:5)

3 units, not given 2000-01

50. Astronomy Laboratory and Observational Astronomy—The theory and use of the optical telescope and the interpretation of basic observational data of planets, stars, and galactic systems. Individual observations with a 24-inch Cassegrain telescope are supplemented by lectures/discussion of basic observational techniques, astronomical catalogs and coordinate systems, and the relation of observations to astrophysical models. Limited enrollment. Lab. GER:2a (DR:5)

3-4 units, Aut, Sum (Staff)

59N. Stanford Introductory Seminar: 21st-Century Physics—Current Topics of Research—Preference to freshmen. Supplements 59. Discussion, reading, and writing on areas of physics research currently active: neutrinos, Bose-Einstein condensates, high temperature superconductors, the fate of the universe.

1 unit, Aut (Dimopoulos)

81Q. Stanford Introductory Dialogue: Lookback Time in Cosmology—Preference to sophomores. The use of telescopes as "time machines" to see the history of the universe. Summary of the big bang, and galaxies and quasars at high redshift. How old is the universe? When did the first objects form? When were the elements created? What is the cosmic dark matter? Can we predict the future evolution of the cosmos? Discussion is at a semi-quantitative level: basic physics concepts are used without calculus. Directed reading, sample exercises, and (weather permitting) a term project observing distant galaxies and quasars at the Stanford teaching observatory. Prerequisites: elementary physics (21-25 or equivalent).

1 unit, Aut (Romani)

82Q. Stanford Introductory Dialogue: Expanding Cosmic Horizons—Preference to sophomores. The history and structure of our cosmic environment. How recent advances in observations at various wavelengths are expanding the horizons of our knowledge. Possible topics: What are the properties of black holes? What is the nature, amount, and distribution of the "dark matter" which appears to dominate the universe? What is the geometry and fate of the universe? Prerequisite: freshman physics or equivalent.

1 unit, Spr (Wagoner)

100. Introduction to Observational and Laboratory Astronomy—Introduction to observational techniques in astronomy for physical science or engineering students. Emphasis is on the measurement of fundamental astronomical parameters such as distance, temperature, mass, and composition of stars. Lecture and observation using the 24-inch telescope at the Stanford Student Observatory. Limited enrollment. Prerequisites: one year of physics; prior or concurrent registration in 25, 65, or 70; and consent of instructor. GER:2a (DR:5)

4 units, Spr (Staff)

160. Introduction to Stellar and Galactic Astrophysics—Physics of the sun. Evolution and death of stars. White dwarfs, novae, planetary nebulae, supernovae, neutron stars, pulsars, binary stars, x-ray stars, and black holes. Galactic structure: interstellar medium, molecular clouds, HI and HII regions, star formation and element abundances. Prerequisites: calculus and one year of college physics at the level of the Physics 40 series or equivalent.

3 units, Aut (Petrosian)

161. Introduction to Extragalactic Astrophysics and Cosmology—Observations of the distances and compositions of objects on cosmic scales: galaxies, galaxy superclusters, quasars, and diffuse matter at high redshift. Big bang cosmology, including cosmic expansion, the origin of matter and the elements, inflation, and creation of structure in the universe. Observational evidence for dark matter. Models for the fate of the universe. Emphasis is on physical processes in the early universe. Prerequisites: calculus and one year of college physics at the level of the 40 series.

3 units, Spr (Church)

162. Planetary Exploration—(Enroll in Electrical Engineering 106.)

3 units, Spr (Fraser-Smith)

169A,B,C. Independent Study in Astrophysics and Honors Thesis—Detailed study of a selected problem in astrophysics with one or more faculty members. While not all projects require three quarters, the sequence below suggests the format most projects are expected to follow. Projects may commerce in any quarter.

169A. Selection of the Problem—Selection of the problem to be studied and development of the theoretical apparatus or initial interpretation of the selected problem. Preparation of a detailed description of the problem and its background and a comprehensive discussion of the work planned in the subsequent two quarters.

1-9 units, Aut (Staff)

169B. Continuation of Project—Substantial completion of the required computations or data analysis for the research project selected.

1-9 units, Win (Staff)

169C. Completion of Project—Completion of research and writing of a detailed paper presenting methods used and results.

1-9 units, Spr (Staff)

PHYSICS

11N. Stanford Introductory Seminar: Symmetries of Nature—From Inner Space to Outer Space—Preference to freshmen. Physicists use symmetry principles to discover the laws of nature on a subatomic scale and how these symmetries determine the behavior of matter on microscopic scales of atoms, nuclei, and elementary particles. In parallel with understanding subatomic scales (Inner Space), understanding the structure and development of the universe (Outer Space) has undergone radical revisions. Observations of the motions of galaxies have led to the conclusion that the universe began with an instantaneous, enormous explosion, about 12 billion years ago. The status of the quest to unify the fundamental interactions (electromagnetic, weak, strong, and gravitational) observed in Nature into a unified Theory of Everything. The impact of this quest to understand Inner Space on understanding the origin and evolution of the universe. Discussions are semiquantitative. Term project paper. Prerequisite: high school physics or equivalent.

2 units, Aut (Gratta)

12Q. Stanford Introductory Seminar: Science, Society, and Politics—Preference to sophomores. Scientific research has a profound impact on society, and society has come to expect solutions to important social issues. The public debates on the major science-related issues of the day: global warming and ozone depletion; the danger posed by earth-asteroid collisions; the cancellation of the Super-conducting Supercollider; the U.S. decision to build the Space Station jointly with Russia; "clean" nuclear power from fusion; cosmology and the Hubble telescope; the debate on manned exploration of Mars; the search for extraterrestrial life; the debate on the appropriate level of funding for scientific research; and cooperation and competition between science and the humanities. Offered occasionally.

4 units, not given 2000-01

19. How Things Work: An Introduction to Physics—Non-technical survey of the methodology of physics and some of the achievements in understanding the physical world. Physics is explored by observing its impact on everyday life. Emphasis is hands-on experience through class demonstrations and other practical activities. Prerequisite: high school algebra and trigonometry.
3 units, Win (Fisher)

21. Mechanics and Heat—For biology, social science, and premedical students. Introduction to Newtonian mechanics, fluid mechanics, theory of heat. Calculus is used as a language and developed as needed. Prerequisites: working knowledge of elementary algebra and trigonometry. GER:2a (DR:5)
3 units, Aut (Wojcicki)

22. Mechanics and Heat Laboratory—Pre- or corequisite: 21.
1 unit, Aut (Wojcicki)

23. Electricity and Optics—Electric charges and currents, magnetism, induced currents; wave motion, interference, diffraction, geometrical optics. Prerequisite: 21. GER:2a (DR:5)
3 units, Win (Church)

24. Electricity and Optics Laboratory—Pre- or corequisite: 23.
1 unit, Win (Church)

25. Modern Physics—Introduction to modern physics. Relativity, quantum mechanics, atomic theory, radioactivity, nuclear reactions, nuclear structure, high energy physics, elementary particles, astrophysics, stellar evolution, and the big bang. Prerequisite: 23 or consent of instructor. GER:2a (DR:5)
3 units, Spr (Susskind)

26. Modern Physics Laboratory—Pre- or corequisite: 25.
1 unit, Spr (Susskind)

28. Mechanics, Heat, Electricity, and Magnetism I—For biology, social science, and premedical students. The sequence 28 and 29 fulfills, in ten weeks, the one-year college physics requirement (with lab) of most medical schools. Topics: Newtonian mechanics, fluid mechanics, theory of heat, electric charges, and currents. Calculus is used as a language and developed as needed. Prerequisite: working knowledge of elementary algebra and trigonometry. GER:2a (DR:5)
6 units, Sum (Fisher)

29. Electricity and Magnetism II, Optics, Modern Physics—Magnetism, induced currents; wave motion, optics; relativity, quantum mechanics, atomic theory, radioactivity, nuclear structure and reactions, elementary particles, astrophysics, and cosmology. Prerequisite: 28. GER:2a (DR:5)
6 units, Sum (Fisher)

41. Mechanics—Vectors, particle kinematics and dynamics, work, energy, momentum, angular momentum; conservation laws; rigid bodies. Discussions based on use of calculus. Corequisite: Mathematics 19 or 41, or consent of instructor. GER:2a (DR:5)
3 units, Aut (Schwettman)

41N. Stanford Introductory Seminar: Mechanics—Insights, Applications, and Advances—Preference to freshmen. Faculty led and associated with 41, with student participation. Possible topics: tidal forces, gyroscopic effects, fractal dimensions, and introduction to chaos. Enrollment limited to 20 in one section. Corequisite: 41 or advanced placement.
1 unit, Aut (Romani)

43. Electricity—Mechanical waves. Electrostatics including fields, potentials, capacitors, and dielectrics. Steady state currents, and circuits with batteries and resistors. RC circuits. Prerequisites: 41, and Mathematics 19 or 41. Corequisite: Mathematics 20 or 42, or consent of instructor. GER:2a (DR:5)
3 units, Win (Cabrera)

43N. Stanford Introductory Seminar: Electricity—Understanding Electrical Phenomena—Preference to freshmen. Expands on the material presented in 43, discussing a variety of phenomena associated with electricity and magnetism, and allowing students to connect the material in 43 with the world in which they live. Corequisite: 43 or advanced placement.
1 unit, Win (Osheroff)

45. Magnetism—Time varying currents and fields, inductance, Maxwell's equations, electromagnetic oscillations and waves. Special relativity. Prerequisite: 43. GER:2a (DR:5)
3 units, Spr (Michelson)

45N. Stanford Introductory Seminar: Special Topics in Electromagnetism—Preference to freshmen. Expands on the material presented in 45, discussing a variety of phenomena associated with electricity and magnetism, and allowing students to connect the material in 45 with the world in which they live. Special topics related to recent developments in experimental and theoretical physics. Corequisite: 45 or advanced placement.
1 unit, Spr (Schwettman)

46. Electricity and Magnetism Laboratory—Pre- or corequisite: 45.
1 unit, Spr (Michelson)

47. Light and Heat—Reflection and refraction of light, lens systems; light and electromagnetic waves; temperature, properties of matter, introduction to kinetic theory of matter. Prerequisites: 45 and Mathematics 51, or consent of instructor. GER:2a (DR:5)
4 units, Aut (Osheroff)
Sum (Pam)

48. Light and Heat Laboratory—Pre- or corerequisite: 47.
1 unit, Aut (Osheroff)
Sum (Pam)

59N. Current Research Topics—Recommended for all prospective physics majors. Major areas of current research. Topics: fundamental particles, solid state physics, low temperature physics, biophysics, and astrophysics. Lectures by faculty and physicists with research interests in these fields.
1 unit, Aut (Dimopoulos)

61,63,65. Advanced Freshman Physics—Recommended for students contemplating a major in Physics and other students interested in a more rigorous treatment of physics. The fundamental structure of classical physics including Newtonian mechanics, special relativity, and electricity and magnetism; selected topics in heat and light in Spring Quarter. Lectures and small discussion sections. Prerequisites: high school physics and familiarity with calculus (differentiation and integration in one variable); prior or concurrent registration in Mathematics 42. Physics 61, 63, and 65 are all GER:2a (DR:5)
61. *4 units, Aut (Moler)*
63. *4 units, Win (Dimopoulos)*
65. *4 units, Spr (Kallosh)*

61N. Stanford Introductory Seminar: Mechanics—Insights, Applications, and Advances—Preference to freshmen. Faculty led and associated with 61, with student participation. Possible topics: tidal forces, gyroscopic effects, fractal dimensions, and introduction to chaos. Enrollment limited to 20 in one section. Corequisite: 61.
1 unit, Aut (Romani)

63N. Stanford Introductory Seminar: Applications of Electromagnetism—Preference to freshmen. Faculty led and associated with 63, including material related to the 63, but at a slightly more advanced level. Student participation is encouraged in the selection of topics. Enrollment limited to 20 in one section. Corequisite: 63.

1 unit, Win (Thomas)

64,66. Advanced Freshman Physics Laboratories—Experimental work in mechanics, electricity and magnetism, and optics. Prerequisite: 61.

64. *1 unit, Win (Dimopoulos)*

66. *1 unit, Spr (Kallosh)*

65N. Stanford Introductory Seminar: Statistical Mechanics—Principles and Applications—Preference to freshmen. Faculty led and associated with 65, including material related to 65, but at a slightly more advanced level. Concepts about thermal and statistical physics, examples, and applications. Enrollment limited to 20 in one section. Corequisite: 65.

1 unit, Spr (Roodman, Staff)

70. Modern Physics—Relativity, the experimental basis of quantum theory, Schrödinger equation, atomic structure, nuclear structure, high energy physics, elementary particles. Prerequisite: 45. Recommended: prior or concurrent registration in Mathematics 53 or 130. GER:2a (DR:5)

3 units, Aut (Kapitulnik)

72. Modern Physics Laboratory—Pre- or corequisite: 25 or 70.

1 unit, Aut (Kapitulnik)

80N. Stanford Introductory Seminar: The Technical Aspects of Photography—Preference to freshmen. For those with some background in photography. How cameras record photographic images on film and electronically. The technical photographic processes which the photographer must understand in order to use cameras effectively. Camera types and their advantages, how lenses work and their limitations, camera shutters, light meters and the proper exposure of film, film types, depth of focus, control of the focal plane and perspective, and special strategies for macro and night photography. View cameras and range finder technical cameras. Students exploit the flexibility of these formats to take photographs around campus. Prerequisite: knowledge of elementary physics.

3 units, Spr (Osheroff)

83Q. Stanford Introductory Seminar: The Physics of Terrorist Bomb Detection—Preference to sophomores. The bombing of Pan Am 103 over Lockerbie, Scotland in December 1988 has pushed efforts to develop a suitable bomb detector to protect airplanes, buildings, tunnels, and other terrorist targets. The limitations imposed on a successful detection system, and the physics principles already tried or under development. Site visits are made to industrial laboratories engaged in making bomb detectors. Prerequisite: high school background in physics.

3 units

84Q. Stanford Introductory Dialogue: On Growth and Form—Preference to sophomores. Introduces important concepts in physics by analyzing the shapes of objects and growth mechanisms from a statistical mechanics point of view. Concepts such as self similarity, fractals, and random processes describe the objects. Simple computer simulations study and visualize objects. Demonstrations by instructor and the students.

1 unit

105,106,107. Intermediate Physics Laboratory Seminars—Sequence in experimental techniques required of all Physics majors. Topics: electronics, detectors and radioactive sources, optics and lasers, statistics and data handling. Lectures/labs. 106 consists of independent experiments. Prerequisites: 46 or 64 and 66; prior or concurrent registration in 48 and the 120 series.

105. Laboratory Seminar I: Electronics

3 units, Aut (Pam)

106. Laboratory Seminar II: Particle Physics Experimental Techniques

3 units, Win (Moler)

107. Laboratory Seminar III: Optics—(WIM)

3 units, Spr (Fejer)

110,111. Intermediate Mechanics—The mechanics of systems of particles and rigid bodies. Coordinate transformation and vectors; Newtonian mechanics; linear and nonlinear oscillations; Hamilton's principle, Langrangian and Hamiltonian dynamics; central forces, planetary motion; collisions; non-inertial reference systems; rigid body dynamics; coupled oscillations; and introductory fluid mechanics. Prerequisites: 41 or 61, and Mathematics 53 or 130.

110. *4 units, Win (Shen)*

111. *4 units, Spr (Vuletic)*

120,121,122. Intermediate Electricity and Magnetism—Vector analysis, electrostatic fields, including multipole expansion; dielectrics. Special relativity and transformation between electric and magnetic fields. Maxwell's equations. Static magnetic fields, magnetic materials. Electromagnetic radiation, plane wave problems (free space, conductors and dielectric materials, boundaries). Dipole and quadrupole radiation. Wave guides and cavities. Prerequisites: 45 or 63; concurrent or prior registration in Mathematics 53, 130 or 131 with Physics 120 and 121, respectively. Recommended: concurrent or prior registration in Mathematics 103.

120. *4 units, Aut (Peskin, Staff)*

121. *4 units, Win (Peskin, Staff)*

122. *4 units, Spr (Peskin, Staff)*

130,131,132. Quantum Mechanics—The origins of quantum mechanics, wave mechanics, and the Schrödinger equation. Heisenberg's matrix formulation of quantum mechanics, solutions to one-dimensional systems, separation of variables and the solution to three-dimensional systems, the central field problem and angular momentum eigen-states, spin and the coupling of angular momentum, Fermi and Bose statistics, perturbation theory and other approximation techniques. Scattering theory: partial wave expansion, Born approximation, Green's functions. Reference to problems in atomic and nuclear physics explaining the basic phenomenology of these disciplines. Invariance principles and conservation laws in the context of quantum theory. Prerequisites: 70 or equivalent and 110, 111; concurrent or prior registration in 120, 121, 122, and Mathematics 53 or 130, 131.

130. *4 units, Aut (Burchat)*

131. *4 units, Win (Burchat)*

132. *4 units, Spr (Fetter)*

135. Computational Physics—The development of computational methods with application to problems in classical, electro-, quantum, and statistical mechanics. Numerical integration; solution of ordinary differential equations including the Runge-Kutta method; solutions of the heat equation and Poisson's equation with relaxation methods, etc.; Monte Carlo methods; matrix methods and eigenvalue problems. Short introduction to Basic programming; class projects may be programmed in Basic, Fortran Pascal, or C. Offered occasionally. Prerequisites: 110, 111, 121; Mathematics 53 or 130.

3 units, Aut (Doniach)

150. Applied Quantum Mechanics I—(Graduate students register for 222; enroll in Applied Physics 150.)

4 units, Aut (Miller)

151. Applied Quantum Mechanics II—(Graduate students register for 223; enroll in Applied Physics 151.)
4 units, Spr (Miller)

152. Introduction to High Energy Physics—(Graduate students register for 252.) The elementary-particle phenomena. Leptons and their interactions. The quark model. Quantum numbers and their flow in the fundamental interactions. The kinematics and dynamics of particle collisions at high energy. Particle accelerators. Methods of detection and identification of elementary particles. Prerequisite: 122.
3 units, Spr (Dixon)

170,171. Thermodynamics, Kinetic Theory, and Statistical Mechanics—The derivation of laws of thermodynamics from basic postulates; the determination of the relationship between atomic substructure and macroscopic behavior of matter. Temperature; equations of state, heat, internal energy; entropy; reversibility; applications to various properties of matter; absolute zero and low-temperature phenomena. Distribution functions, transport phenomena, fluctuations, equilibrium between phases, phase changes, the partition function for classical and quantum systems, Bose-Einstein condensation, and the electron gas. Cooperative phenomena including ferromagnetism, the Ising model, and lattice gas. Irreversible processes. Prerequisites: 47 or admission to Advanced Sequence, and Mathematics 53 or 130.
170. *4 units, Aut (Silverstein, Staff)*
171. *4 units, Win (Laughlin)*

172. Physics of Solids I—Introduction to solid state physics. Crystal properties and the consequence of the periodic nature of solids. Electrons and phonons, elementary band theory, electrical and thermal transport. Semiconductor physics. Prerequisite: 171.
3 units, Spr (Greven)

181. Introduction to Modern Optics—(Enroll in Applied Physics 268.)
3 units, Aut (Byer)

190. Independent Study—Undergraduate research in experimental or theoretical physics under the supervision of a faculty member. Prerequisites: superior work as an undergraduate physics major; approval of the instructor and of the Undergraduate Study Committee of the department.
1-15 units, any quarter (Staff)

192. Introductory Biophysics—(Enroll in Applied Physics 192.)
3 units, alternate years, given 2001-02

201,203. Advanced Physics Laboratory—Experiments in atomic, nuclear, solid state, and low-temperature physics; optics; and particle physics. 201 has individually prepared lab experiments. 203 consists of continued experiments at the advanced physics lab level or preparation of a new experiment. Prerequisites: 105, 107. Recommended: prior or concurrent registration in 171.
3 units, not given 2000-01

204. Senior Seminar in Theoretical Physics—Topics of recent interest in theoretical physics: Bose-Einstein condensation of atoms, high T_e superconductivity of cuperates, quantized Hall effect, quantum chaos, superfluidity of $3H_e$. Work in the seminar may provide a basis for an honors project in theoretical physics. Prerequisite: 132 or consent of instructor.
3 units, Aut (Laughlin)

205. Honors Undergraduate Research—Experimental or theoretical project and thesis in physics under supervision of a faculty member. Planning of the thesis project should begin no later than middle of the junior year. Successful completion of an honors thesis leads to graduation "with departmental honors." Prerequisites: superior work in physics as an undergraduate major and approval of the honors committee.
1-12 units, any quarter (Staff)

GRADUATE

207,208. Laboratory Electronics—(Enroll in Applied Physics 207, 208.)
207. *3 units, Win (Fox)*
208. *3 units, Spr (Fox) alternate years, not given 2001-02*

210. Advanced Particle Mechanics—The Lagrangian and Hamiltonian dynamics of particles (a review), small oscillations, and rigid body motion. Transition to continuum mechanics. Prerequisites: 111, 122.
3 units, Aut (Fetter)

211. Continuum Mechanics—Elasticity, fluids, turbulence, waves, gas dynamics, shocks, and MHD plasmas. Examples from everyday phenomena, geophysics, and astrophysics. Prerequisite: 111.
3 units, Win (Wagoner)

212. Statistical Mechanics—Kinetic theory; evolution of distribution function, transport coefficients. Principles of statistical mechanics; ensembles, statistical equilibrium. Thermodynamic functions, ideal and near-ideal gases, solids. Fluctuations, noise, and irreversible thermodynamics. Phase transitions and cooperative phenomena. Prerequisites: 171, 231.
3 units, Spr (Laughlin)

215. Numerical Methods for Physicists and Engineers—(Enroll in Applied Physics 215.)
3 units, alternate years, given 2001-02

216. Back of the Envelope Physics—Survey of topics intended to develop the ability to do simple, physically based calculations with undergraduate physics. Goal: sharpen ones physical intuition and promote a synthesis of physics at the undergraduate level through the examination of problems normally not usually included in undergraduate physics. Topics: practice in making order of magnitude estimates, applications of statistical mechanics, astrophysics and cosmology, biological physics, scaling concepts in physics, quantum interference and quantum measurement, geophysics, etc. Prerequisites: mechanics, statistical mechanics, electricity and magnetism, and quantum mechanics at the undergraduate level.
3 units, Aut (Linde)

220,221. Classical Electrodynamics—Electrostatics and magnetostatics: conductors and dielectrics, magnetic media, electric and magnetic forces and energy. Maxwell's equations: electromagnetic waves, Poynting's theorem, electromagnetic properties of matter, dispersion relations, wave guides and cavities, magnetohydrodynamics. Special relativity: Lorentz transformations, covariant, equations of electrodynamics and mechanics, Lagrangian formulation, Noether's theorem and conservation laws. Radiation: dipole and quadrupole radiation, electromagnetic scattering and diffraction, the optical theorem, Liénard-Wiechert potentials, relativistic Larmor's formula, frequency and angular distribution of radiation, synchrotron radiation. Energy losses in matter: Bohr's formula, Cherenkov radiation, bremsstrahlung and screening effects, transition radiation. Prerequisites: 122 or equivalent; Mathematics 106 and 132, or concurrent registration in Physics 210 and 211.
220. *3 units, Win (Silbergleit)*
221. *3 units, Spr (Zhang)*

222. Applied Quantum Mechanics I—Graduate section; see 150.
3 units, Aut (Miller)

223. Applied Quantum Mechanics II—(Graduate section; enroll in Electrical Engineering 223.) See 151.
3 units, Spr (Miller)

230,231,232. Quantum Mechanics—Prerequisites: 132 and a strong course on differential equations.

230.—Fundamental concepts. Introduction to Hilbert spaces and Dirac's notation. Postulates are applied to simple systems, including those with periodic structure. Symmetry operations and gauge transformation. The concept of propagators and path integral quantization. Problems related to measurement theory. The quantum theory of angular momenta and central potential problems (hydrogen, quarkonium).

3 units, Aut (Shenker)

231.—Sets a basis for higher level courses on atomic physics, optics, spectroscopy, and particle physics. Wigner-Eckart theorem and addition of angular momenta. Approximation methods for time-independent and time-dependent perturbations. Semiclassical and quantum theory of radiation, second quantization of radiation and matter fields. Systems of identical particles and many electron atoms.

3 units, Win (Chu)

232.—Special topics. Elementary scattering theory (Born approximation, partial wave analyses, resonance scattering). S-matrix formalism. Relativistic single-particle equations. Dirac equation applied to central potentials, relativistic corrections, and nonrelativistic limits.

3 units, Spr (Shenker)

240. Asymptotics Methods in Physics Problems—Use of the notion of asymptotics in physics. Algebraic equations, branching (eigenfrequencies of small oscillations). Asymptotic estimates of integrals (short and long time behavior, near and far field, group velocity and energy transport by waves); uniform asymptotics. Asymptotic methods for ODEs: coordinate and parameter asymptotics, regular and singular perturbations; WKB method (quasiclassic approximation, one-dimensional wave propagation); Poincare method, "fast" and "slow" variables (perturbation of periodic orbits, weak dissipation, adiabatic invariants); matched asymptotic expansions—boundary layers (problems of electrostatics, heat conductivity, elasticity, etc.). Asymptotic methods for PDEs: ray method for multi-dimensional linear wave propagation (rays, wavefronts, least-time path principle, caustics for waves of different physical origin); matched asymptotic expansions—boundary layers and "thin" bodies (applications to electrostatics, hydrodynamics and MHD, linear elasticity, etc.); multi-scale expansions: homogenization, effective parameters for composite bodies. Examples from various branches of physics (astrophysics and general relativity).

3 units

252. Introduction to High Energy Physics—Graduate section; see 152.

3 units, Spr (Dixon)

260. Introduction to Astrophysics—The basic properties of stars, galaxies, and the universe. Physical processes for production of radiation from cosmic sources. The structure and evolution of the universe and its constituent galaxies and stars. Models of the early universe and the relation between particle physics and cosmology. Prerequisites: 111, 122, 171.

3 units

262. Introduction to Gravitation—Tensor analysis: special relativity, the energy-momentum tensor, and curvature. Einstein's equations: weak fields, tests, spherically-symmetric solutions, gravitational waves. Cosmology, black holes, stellar structure, and other topics in astrophysics, as time permits. Prerequisites: 111, 122**.**

3 units

271. Introduction to Solid State Physics—Reviews key discoveries in condensed matter physics in the past 15 years, with emphasis on experiment. Topics: sliding charge density waves in layer compounds, the first pressure-induced Mott transition, the first organic superconductor, the discovery of superfluid $3H_e$, quasicrystals, the Sharvin effect, the quantum hall effect, and re-entrant superconductivity. Journal club format, with presentations by students on assigned topics. Offered occasionally.

3 units

272. Solid State Physics: Survey—(Enroll in Applied Physics 272.)

3 units, Aut (Harrison)

273. Solid State Physics—(Enroll in Applied Physics 273.)

3 units, Win (Harrison)

290. Research Activities at Stanford—Required of all first-year physics graduate students and strongly suggested for junior physics majors for 1 unit; no registration needed for graduate students. Review of research activities in the department and elsewhere at Stanford at a level suitable for entering graduate students.

1-3 units, Aut (Gratta)

291. Practical Training—Opportunity for practical training in industrial labs. Arranged by student with the research adviser's approval. A brief summary of activities is required, approved by the research adviser.

3 units, Sum (Staff)

293. Literature of Physics—Intensive study of the literature of any special topic. Preparation, presentation of reports. If taken under the supervision of a faculty member outside the department, approval of the Physics chair required. Prerequisites: 25 units of college physics, consent of instructor.

1-15 units, any quarter (Staff)

294. Teaching of Physics Seminar—Required of all teaching assistants in Physics prior to or concurrent with the first quarter of a teaching appointment; registration not required. Techniques of teaching physics by means of weekly seminars/discussions, simulated teaching situations, and evaluation of in-class teaching performance.

1 unit, Aut (Pam)

301. Astrophysics Laboratory—Combined seminar/lab investigating the fundamental observational basis of physical models of astronomical objects. Observational component uses the 24-inch telescope at the Stanford Observatory and ancillary photometric and spectroscopic instrumentation. Emphasis is on spectroscopic and photometric observation of main sequence, post-main sequence, and variable stars. Limited enrollment. Offered occasionally. Prerequisite: consent of instructor.

3 units, Sum (Staff)

312. Basic Plasma Physics—For the nonspecialist who needs a working knowledge of plasma physics for space science, astrophysics, fusion, or laser applications. Topics: orbit theory, the Boltzmann equation, fluid equations, MHD waves and instabilities, EM waves, the Vlasov theory of ES waves and instabilities including Landau damping and quasilinear theory, the Fokker-Planck equation, and relaxation processes. Advanced topics in resistive instabilities and particle acceleration. Prerequisite: 210 or 220, or consent of instructor.

3 units, Spr (Staff)

320. Quantum Optics and Selected Topics in Atomic Physics—Quantization of the electromagnetic field, photon states, and vacuum fluctuations and atomic transitions of real atoms. Two-level atoms, the Optical Bloch Equations, dressed states, coherent transients, resonance fluorescence, laser cooling and trapping of atoms and ions, tests of quantum mechanics and Bell's Theorem, photon statistics, coherence, antibunching, squeezed states, and parity non-conservation and time-reversal invariance tests in atomic physics. Offered occasionally.

3 units

321. Laser Spectroscopy—Theoretical concepts and experimental techniques of modern laser spectroscopy. Absorption, dispersion, Kramers-Kronig relations, line-shapes. Classical and laser linear spectroscopy. Semiclassical theory of laser atom interaction: time-dependent perturbation theory, density matrix, optical Bloch equations, coherent pulse propagation, multiphoton transitions. High-resolution nonlinear laser spectroscopy: saturation spectrosopy, polarization spectroscopy, two-

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photon and multiphoton spectroscopy, optical Ramsey spectroscopy. Semiclassical theory of the laser. Phase conjugation. Four-wave mixing, harmonic generation. Coherent Roman spectroscopy, quantum beats, ultra-sensitive detection. Offered occasionally. Prerequisite: 230. Recommended: 231.
3 units

323. Laser Cooling and Trapping—The fundamental principles of laser cooling and atom trapping. The general treatment of optical forces on atoms, the various forms of laser cooling, atom optics and atom interferometry, ultra-cold collisions, and Bose condensation of dilute gases. Emphasis is on the development of the general formalisms currently used to treat these topics. Applications of the cooling and trapping techniques: atomic clocks, internal sensors, measurements that address high-energy physics questions, studies of many-body effects, polymer science, and biology. Prerequisite: 231 or equivalent.
3 units

324. Introduction to Accelerator Physics—(Enroll in Applied Physics 324.)
3 units, alternate years, given 2001-02

330,331,332. Quantum Field Theory—Introduction to the concepts and methods of quantum field theory. Prerequisites: 210, 221, 232.

330.—Quantization of scalar and Dirac fields. Feynman diagrams. Quantum electrodynamics. Elementary electrodynamic processes: Compton scattering, e+e- annihilation. Soft photons and infrared divergences.
3 units, Aut (Kallosh)

331.—Loop diagrams, electron (g-2), renormalization, Ward Identities, the renormalization group, perturbation theory anomalies.
3 units, Win (Kallosh)

332.—Local gauge invariance, Yang-Mills fields, spontaneous symmetry breaking and the Higgs mechanism, functional integral methods, quantization of Yang-Mills fields, asymptotic freedom. Quantum chromodynamics.
3 units, Spr (Linde)

351,352. Elementary Particle Physics—The phenomena of elementary particle interactions and their theoretical interpretation. Offered occasionally. Prerequisite: 330.

351. Introduction to the Standard model—Features of high-energy interactions of hadrons; deeply inelastic lepton-hadron scattering; structure functions; the parton model; QCD, gluons, and scaling violations; jets and quark fragmentation in rr(LC) and e+e- annihilation to hadrons; radiative corrections in QED and QCD; running coupling constants; experimental measurements of the strong coupling; Monte Carlo techniques.
3 units

352.—Hadron spectroscopy in the static quark model; properties of heavy quarks and quarkonium systems. Weak interactions: muon, pion, and beta decay; weak mixing angles; the K_L-K_S system on CP violation; charged and neutral current neutrino scattering; the standard model of electroweak interactions; determinations of $\sin_2(q)_W$; properties of W and Z bosons; guage symmetries and the Higgs mechanism; properties of Higgs particles. Introduction to topics beyond the standard model: grand unification, proton decay, super-symmetry.
3 units

360. Physics of Astrophysics—Theoretical concepts and tools for modern astrophysics. Radiation transfer equations, and scattering and absorption processes: Compton, synchrontron photoionization, lines, and Bremsstrahlung. Equations of state of ideal, interacting, and degenerate gasses. Particle kinetic equations (Boltzmann, Fokker-Planck) and mechanisms for particle acceleration and transport. Application to ionization and dust scattering in HII regions and high-energy astrophysics sources such as accretion disks, x-ray and radio sources. Prerequisites: 122, 171.
3 units, Win (Petrosian)

361. Stellar and Galactic Astrophysics—Basic astronomical data on stars, star clusters, interstellar medium, and the Milky Way galaxy. Basic theory of stellar structure; hydrostatic equilibrium, radiation balance, and energy production. Stellar formation, Jean's mass and protostars. Evolution of stars to the main sequence and beyond to red giants, white dwarfs, neutron stars, and black holes. Structure of the Milky Way; the disk and spiral arms, central bulge or bar, black hole, the halo, and mass of the galaxy. Prerequisites: 221, and 260 or 360.
3 units, Spr (Petrosian)

362. Extragalactic Astrophysics and Cosmology—Basic observational data on galaxies and their activities, cosmic microwave background radiation, gravitational lensing and dark matter in the universe. Models of the origin, structure, and evolution of the universe based on the theory of general relativity. Test of the models. Physics of the early universe, inflation, Baryosynthesis, nucleosynthesis, and galaxy formation. Prerequisites: 210, 211, 260 or 360, 262.
3 units

363. Solar and Solar-Terrestrial Physics—Structure, mechanisms, and properties of the sun's interior and atmosphere; solar wind and its variability; solar activity; coronal mass ejections; UV, x-ray, and high-energy particle emission. Earth's magnetosphere. The interaction of the solar wind with the earth's magnetosphere and its terrestrial effects. The sun's electromagnetic radiation effect on the terrestrial environment. Prerequisite: 221 or equivalent.
3 units (Kosovichev) alternate years, given 2001-02

364. Advanced Gravitation—Fundamental principles and experiments. Differential geometry. General structure of Einstein's equations. Major applications from: cosmology, stars, black holes, generation and detection of gravitational radiation. Prerequisites: 220, 221.
3 units, Aut (Wagoner)

370. Theory of Many-Particle Systems—Application of quantum field theory to the nonrelativistic, many-body problem, including methods of temperature-dependent Green's functions and canonical transformations. Theory of finite-temperature, interacting Bose and Fermi systems with applications to superfluidity, superconductivity, and electron gas. Offered occasionally. Prerequisite: 232.
3 units

372. Condensed Matter Theory I—**(**Enroll in Applied Physics 372.)
3 units, alternate years, given 2001-02

373. Condensed Matter Theory II—**(**Enroll in Applied Physics 373.)
3 units, alternate years, given 2001-02

376. Superfluidity and Superconductivity—Introduction to superfluid H_e: two-fluid model, phonons, and rotons, Feynman description, vortices, Bogoliubov theory. Phenomenology of superconductors: London description, Ginzburg-Landau model, type-I vs. type-II materials, Josephson effects, thin films, Kosterlitz-Thouless behavior, electron-phonon coupling. BCS theory: bulk systems, tunneling, strong-coupling materials, dirty and gapless superconductivity, fluctuation effects, Ginzburg criterion. Offered occasionally. Recommended: Applied Physics 272, 273, or equivalents.
3 units

377. Literature of Condensed Matter Physics—Review of key discoveries in condensed matter physics in the past 15 years, with emphasis on experiment. Topics: sliding charge density waves in layer compounds, the first pressure-induced Mott transition and organic superconductor, the discovery of superfluid $3H_e$, quasicrystals, the Sharvin effect, the

Quantum Hall effect, and reentrant superconductivity. Journal club format with presentations by students on assigned topics. Offered occasionally.

3 units

383. Introduction to Atomic Processes—(Enroll in Applied Physics 383.)

3 units, alternate years, given 2001-02

387. Quantum Optics and Measurements—(Enroll in Applied Physics 387.)

3 units, alternate years, given 2001-02

388. Mesoscopic Physics and Nanostructures—(Enroll in Applied Physics 388.)

3 units, Win (Yamamoto)

392. Topics in Molecular Biophysics—(Enroll in Applied Physics 392.)

3 units, Win (Doniach) alternate years, not given 2001-02

450,451,452. Theoretical Physics of Particles and Fields—Advanced topics in theoretical high-energy physics. Topics change by quarter and year to provide a background in all areas of current theoretical research. Prerequisite: 332.

450. M-Theory Compactifications and Duality

3 units, not given 2000-01

451. Elements of String Theory

3 units, Win (Susskind)

452. Strings, Branes, and Duality

3 units, Spr (Dimopoulos)

459. Frontiers in Interdisciplinary Biosciences—(Cross-listed in multiple departments in the schools of Humanities and Sciences, Engineering, and Medicine; students should enroll directly through their affiliated department, if at all possible.) Introduction to cutting-edge research involving interdisciplinary approaches to bioscience and biotechnology; for specialists and non-specialists. Associated with Stanford's Clark Center for Interdisciplinary Bioscience, and held in conjunction with a seminar series meeting twice monthly during 2000-01. Leading investigators from Stanford and throughout the world speak on their research; students also meet separately to present and discuss the ever-changing subject matter, related literature, and future directions. Prerequisite: keen interest in all of science, with particular interest in life itself. Recommended: basic knowledge of biology, chemistry, and physics.

2 units, Aut, Win, Spr (S. Block)

463. Special Topics in Astrophysics—Research-level discussions of current topics in astrophysics. Content varies each quarter and year, depending on the interests of staff and students. Topics to be announced. Offered occasionally.

3 units

473A. Condensed Matter Physics—(Enroll in Applied Physics 473A.)

2 units, Aut (Greven)
Spr (Kapitulnik)

473B. Physics of Disordered Systems—(Enroll in Applied Physics 473B.)

3 units, Win (Kapitulnik)

473C. Physics of Strongly Correlated Electron Systems—(Enroll in Applied Physics 473C.)

3 units, Spr (Doniach)

490. Research Orientation—Familiarizes students with the activities of one or more research groups, within the department or outside. Registration limited to one quarter per research group with overall limitation of two quarters. Prerequisite: consent of student's adviser.

1-15 units, any quarter (Staff)

491. Research—Open only to graduate physics major students, with consent of instructor. Work is in experimental or theoretical problems in research, as distinguished from independent study of a non-research character in 190 and 293. If taken under the supervision of a faculty member outside the department, Physics Graduate Study Committee approval required.

1-15 units, any quarter (Staff)