UNSW Course Outline

PHYS4143 Topics in Contemporary Physics - 2024

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General Course Information

Course Code : PHYS4143
Year : 2024
Term : Term 2
Teaching Period : T2
Is a multi-term course? : No
Faculty : Faculty of Science
Academic Unit : School of Physics
Delivery Mode : In Person
Delivery Format : Standard
Delivery Location : Kensington
Campus : Sydney
Study Level : Undergraduate
Units of Credit : 12

Useful Links
Handbook Class Timetable

Course Details & Outcomes

Course Description

Students will take two of the four lecture modules offered in general relativity; quantum field theory; astrophysics; and quantum matter, information and computing.

Quantum Matter, Information and Computing will introduce students to quantum computing, the physics of superconducting devices, the Quantum Hall and other topological effects in materials, and the basics of Fermi liquid theory. Advanced topics will include Andreev scattering at semiconductor-superconductor interfaces and Majorana fermions, fractional quantum Hall effect, graphene and the two-dimensional Dirac equation.

The Advanced Astrophysics module develops in-depth knowledge of topics in modern Astrophysics and equips students with a modern toolset to engage in cutting-edge research. Students obtain a core understanding of the physics of relevant equations and develop fundamental physics intuition. Topics include: radiative transfer; exoplanets; asteroseismology; interstellar medium and star formation; galaxy formation and evolution; cosmology; time-domain astrophysics; statistical techniques.

Quantum field theory is an important tool in many branches of theoretical physics. In fundamental physics, the QFT framework combines special relativity and quantum mechanics to explain the subatomic structure of matter and the physics of the early universe. In condensed matter physics, it provides a quantum description of many-body systems. This first course in QFT comprises an introduction to classical field theory, the Euler-Lagrange equations and Noether's theorem, the Dirac and Klein-Gordon equations, the quantisation of free scalar, vector and spinor fields; and a selection of topics drawn from covariant perturbation theory, the S-matrix and Feynman diagrams; the computation of elementary processes in quantum electrodynamics; field theory approach to phase transitions; dimensional reduction in classical criticality; critical indexes in low-dimensional systems; non-linear sigma-model and topological solutions.

The General Theory of Relativity is Einstein's geometric theory of gravitation that unifies the Special Theory of Relativity and Newton's law of gravitation. This first course in General Relativity will provide an introduction to non-Euclidean geometry, Einstein's equation; spherically symmetric solutions of Einstein's equations (Schwarzschild solution), the weak field limit; Gravitational collapse, black holes; linearised gravity, gravitational waves and their production and observation; Friedmann-Lemaitre-Robertson-Walker cosmology, the standard hot Big Bang model.

Course Aims

Students is this course will study a range of topics in modern physics. This will provide students with a broad and comprehensive understanding in these areas and a foundation for further study and research. Students will gain skills in analysing current research literature and presenting their analysis in a seminar.

Course Learning Outcomes

Course Learning Outcomes
CLO1 : Recall and demonstrate understanding of core principles of selected topics in physics, such as general relativity, astrophysics, quantum field theory and Quantum Matter, Information and Computing
CLO2 : Develop an ability to analyze and solve a wide range of problems in areas such as general relativity, astrophysics, quantum field theory, quantum matter and information and computing
CLO3 : Communicate disciplinary knowledge and research findings in oral form.
CLO4 : Analyze and evaluate selected peer reviewed journal articles; demonstrate an ability to recognize the important points and explain these to peers.

Course Learning Outcomes	Assessment Item
CLO1 : Recall and demonstrate understanding of core principles of selected topics in physics, such as general relativity, astrophysics, quantum field theory and Quantum Matter, Information and Computing	• Final Exam • Assignments • Journal Club
CLO2 : Develop an ability to analyze and solve a wide range of problems in areas such as general relativity, astrophysics, quantum field theory, quantum matter and information and computing	• Final Exam • Assignments
CLO3 : Communicate disciplinary knowledge and research findings in oral form.	• Journal Club
CLO4 : Analyze and evaluate selected peer reviewed journal articles; demonstrate an ability to recognize the important points and explain these to peers.	• Journal Club

Learning and Teaching Technologies

Moodle - Learning Management System

Assessments

Assessment Structure

Assessment Item	Weight	Relevant Dates
Final Exam	60%	
Assignments	30%	
Journal Club	10%	

Assessment Details

Final Exam

<u>Assessment Overview</u>

Two final exams (one for each topic). Each will be a 2 hour closed book exam, which will contribute 30% to the final grade. Each exam will consist of a number of quantative problems relating to the theory and applications of Quantum Field Theory; General Relativity; Astrophysics; and/or Quantum Matter.

Student advised of marks

<u>Course Learning Outcomes</u>

- CLO1 : Recall and demonstrate understanding of core principles of selected topics in physics, such as general relativity, astrophysics, quantum field theory and Quantum Matter, Information and Computing
- CLO2 : Develop an ability to analyze and solve a wide range of problems in areas such as general relativity, astrophysics, quantum field theory, quantum matter and information and computing

Assignments

<u>Assessment Overview</u>

Four quantitative assignments, worth 30% in total (two assignments worth 15% per topic). Each assignment should require a maximum of 10 hours out-of-class work to complete.

Marked assignments returned with comments

<u>Course Learning Outcomes</u>

- CLO1 : Recall and demonstrate understanding of core principles of selected topics in physics, such as general relativity, astrophysics, quantum field theory and Quantum Matter, Information and Computing
- CLO2 : Develop an ability to analyze and solve a wide range of problems in areas such as general relativity, astrophysics, quantum field theory, quantum matter and information and computing

Journal Club

<u>Assessment Overview</u>

Each student will be assigned a paper (the papers will represent key advances in physics that will be of interest to any serious physicist.). They will make a 20 minute presentation that covers the background, the advance and its implications. Every member of the class will be expected to at least read the paper. The presenter will then lead a discussion (~20 minutes) of the work.

Students will be marked by predefined crieria on their presentation and participation, and given feedback.

Course Learning Outcomes

- CLO1 : Recall and demonstrate understanding of core principles of selected topics in physics, such as general relativity, astrophysics, quantum field theory and Quantum Matter, Information and Computing
- CLO3 : Communicate disciplinary knowledge and research findings in oral form.
- CLO4 : Analyze and evaluate selected peer reviewed journal articles; demonstrate an ability to recognize the important points and explain these to peers.

General Assessment Information

Please see Moodle for a marking rubric for each assessment task.

Assignment Submissions

Unless otherwise specified, assignments should be submitted online by 5pm on the due date.

A downloadable assignment cover sheet is available from https://www.physics.unsw.edu.au/current-students/cover-sheet

Marks will be deducted for late assignments, at a rate of 5% of the maximum possible mark for the assignment per day. A weekend will count as two days. An assignment submitted after the solutions have been posted will automatically receive 0%.

Please see Moodle for details on how feedback will be provided for each assessment task

Grading Basis

Standard

Course Schedule

Attendance Requirements

Students are strongly encouraged to attend all classes and review lecture recordings.

General Schedule Information

Module 1: Advanced Astrophysics

Part 1. Atomic & Molecular Physics, & Radiative Transfer:

Atomic energy levels, allowed and forbidden transitions, partition functions, spectra of hydrogenic atoms, Lorentz and Voigt line profiles. Molecular energy levels and Gaussian profiles, Doppler broadening, pressure broadening. Conditions for local and nonlocal thermodynamic equilibrium. Hot gases: ionization and the Saha equation; cool gases: chemical equilibrium, condensate formation. Single scattering albedo and phase function. Rayleigh scattering, electron scattering. Basic processes of absorption, emission and scattering, optical depth. The radiative transfer equation. Spectral line formation, including the effects of opacity, macro-turbulence and physical conditions on line formation. Examples of line formation in warm and cool atomic gas, and in molecular gas.

Part 2. Exoplanets: Planet formation: conditions in the protostellar disk, condensation temperature, self- shielding, accretion, collisions and scattering, planetary migration and angular momentum transfer. Methods for detecting exoplanets: radial velocity, transits, microlensing, astrometry, observational biases, detecting planetary atmospheres.

Part 3. Asteroseismology: Asteroseismic studies of solar-like oscillators: interior structure, composition, rotation, magnetic field, observational limits.

Part 4. Interstellar Medium and Star Formation: HI in galaxies: hyperfine structure, rotation curves, column density. The phase transition between warm and cool HI, and the formation of molecular gas. HII regions: density, temperature, photoionization, recombination, forbidden transitions, Stromgren radius. The role of turbulence and magnetic fields in the interstellar medium, gravitational collapse, Jeans mass, radiative cooling. Initial mass function. Kennicutt-Schmidt law, core ignition, accretion, Eddington limit, timescales.

Part 5. Galaxy formation and evolution: Orbital dynamics, conservation laws, violent relaxation, stellar populations, galactic chemical evolution. Hierarchical galaxy formation (simulated vs observed), merger trees, galaxy assembly, scaling laws, baryon cycle

Part 6. Time-Domain Astrophysics: Transient phenomena including supernovae, gamma-ray bursts, and the first stars. Gravitational waves (their detection, and models for the originating objects)

Part 7. Advanced statistical techniques: Gaussian mixture modeling, Bayesian statistics, Monte Carlo sampling, forward modelling.

Class Timetable Tuesday 10:00-12:00 (Weeks 1-4,7-10, OMB229) Thursday10:00-11:00 (Weeks 1-4,7-10, OMB229)

Module 2: General Relativity

Part 1: Revision of special relativity (2 hours) Hartle Ch. 4 & 5 Spacetime; Lorentz transformation; Four-vectors; Special relativity kinematics and dynamics; Variational principle for free particle motion; Light rays

Part 2: Gravity as geometry (5 hours) Hartle Ch. 6, 7 & 8 The equivalence principle; Clocks in a gravitational field: heuristic considerations; Specifying geometry with a metric; Newtonian gravity in spacetime/geometry terms;

Local inertial frames and freely falling frames; Light cones and worldlines; Vectors in curved spacetime; Geodesic equation; Riemann normal coordinates

Part 3: Geometry outside a spherical object (4 hours) Hartle Ch. 9 & 12 Schwarzschild geometry; Gravitational redshift; Particle orbits and precession of the perihelion; Light ray orbits and deflection; Schwarzschild black hole; Collapse to a black hole; KruskalSzekeres Coordinates

Part 4: The Einstein equation (6 hours) Hartle Ch. 20, 21 & 22 Vectors and Dual vectors; Tensors; The covariant derivative. Free falling frames; Tidal gravitational force; Equation of geodesic deviation; Riemann curvature; Einstein equation in vacuum; 7 Schwarzschild metric derivation; Density as a source of curvature; Stress-energy tensor; Conservation of energy-momentum; Einstein equation; The Newtonian limit

Part 5: Gravitational waves (3 hours) Hartle Ch. 16 & 23 Linearised gravity in vacuum; Traceless transverse gauge; Linearised Einstein equation with sources; General solution; Gravitational wave production and emission; Gravitational radiation from binary stars; Quadrupole formula; Energy in gravitational waves; Detecting gravitational waves; Gravitational wave interferometers

Part 6: Cosmology (4 hours) Hartle Ch.17 & 18 Cosmological principle; Geometry of a homogeneous and isotropic space; FLRW spacetime and dynamic; Cosmological redshift; Distances and horizons; Inferring distances from observations; Energy content; Friedmann equation; Matter and radiation domination; The age of the universe

Timetable Monday 11:00-13:00 (Weeks 1-4, 7-10, OMB229) Friday 12:00-13:00 (Weeks 1-4, 7-10, OMB229)

Module 3: Quantum Field Theory

Introduction: what is QFT and its relation to many body physics?

Part 1: Second quantization, 2 hours Review of second quantization for scalar and Dirac field; Gupta-Bleuler quantization of the gauge field.

Part 2: Interacting Fields, 4 hours. Lehmann-Symanzik-Zimmermann reduction formula; The Interaction Picture; Greens functions in field theory. Vertex functions and ideas of the diagrammatic technique, Feynman diagrams; Scattering amplitudes (phi^4 theory; QED); S-matrix; Connected diagrams and vacuum bubbles; Cross sections and decay rates.

Part 3: QED processes, 3 hours Derivation of Feynman rules for QED; discussion of important tree-level scattering processes in QED; Gamma matrix algebra.

Part 4: Two-point Green's function, 3 hours. Lehmann - Källén spectral representation; Virtual corrections; Renormalisation

Part 5: Path Integral Approach, 8 hours. Introduction of path integral formulation, path integral approach for many-body systems. Imaginary time formalism. Instantons. Matsubara technique. Wess-Zumino topological terms. False vacuum decay, lifetimes of metastable states. Strongly interacting fermions. Bosonization.

Part 6: Topological objects in field theory, 4 hours. Non-linear sigma model, relevance to quantum antiferromagnets and to the chiral breaking in vacuum. Topological solutions in bosonic field theories. Skyrmions, hopfions. Experimental observations.

Class Timetable Tuesday 14:00-16:00 (Weeks 1-4, 7-10, OMB 229) Thursday 12:00-13:00 (Weeks 1-4, 7-10, OMB G13)

Module 4: Quantum matter, Information and Computing

Part 1: Entanglement, Quantum Phases (3 hours) Kitaev model of Majorana fermions, AKLT model, Density matrix; Entanglement; Schmidt decomposition

Part 2a: Quantum Computing and Error Correction (5 hours), Basics of quantum computation, Basics of quantum error correction, Stabilizer quantum error-correcting codes

Part 2b: Renormalisation group (RG) for classical and quantum systems (4 hours) RG in classical dynamical models: transition to chaos, RG for phase transitions in classical statistical mechanics, Relevance of phase transitions to quantum error-correcting codes, RG for quantum lattice models; Density matrix renormalization group; Matrix product states; Tensor product states

Part 3: Quantum Hall & Topological Effects (4 hours) Charged particle in an electromagnetic field Landau levels and filling factor Integer quantum Hall effect Edge states and topologyFractional quantum Hall effect and composite fermions

Part 4: Quantum Computing (8 hours) Universal set of quantum gates Basic gates - AND, NOT, CNOT Fundamental constraints: no-cloning theorem Quantum error correction: Shor algorithm Making a quantum dot spin qubit Single-qubit operations - sigma_x and sigma_z gates; ESR, EDSR (briefly) Two-qubit operations - exchange, coupling to a resonator, dipole-dipole Theory of decoherence Relaxation: T1 and phonons Dephasing: T2, phonons and noise Spin-echo, pulse sequences Fidelity, randomised benchmarking

Class Timetable Thursday 14:00-16:00 (Weeks 1-4, 7-10, OMB G13) Friday 14:00-15:00 (Weeks 1-4, 7-10, OMB 229)

Course Resources

Prescribed Resources

Astrophysics

Excerpts from appropriate graduate-level textbooks and current research publications will be used as the materials for this course. Current textbooks relevant to these topics are available in the School textbook collection, including:

Clayton, Principles of Stellar Evolution and Nucleosynthesis

Carroll & Ostlie, An Introduction to Modern Astrophysics

Kippenhahn, Weigert, Weiss, Stellar structure and evolution

Binney & Tremaine, Galactic dynamics

Binney & Merrifield, Galactic astronomy

General Relativity:

Primary: J. B. Hartle, Gravity, An Introduction to Einstein's General Relativity

Secondary: S. M. Carroll, An Introduction to General Relativity, Spacetime and Geometry Class

Quantum Field Theory

Schwartz, Quantum Field Theory and the Standard Model

Srednicki, Quantum Field Theory

Altland and Simons, Condensed Matter Field Theory

Sidney Coleman, Aspects of Symmetry

Peskin and Schroeder, An Introduction to Quantum Field Theory Ryder, Quantum Field Theory

Staff Details

Position	Name	Email	Location	Phone	Availability	Equitable Learning Services Contact	Primary Contact
Year coordinator	Michael Schmidt					No	Yes
Convenor	Sarah Martell					No	No
Lecturer	Dennis Stello					No	No
Convenor	Jan Hamann					No	No
Lecturer	Yvonne Wong					No	No
	Oleg Tretiakov					No	No
Convenor	Susan Coppersmith					No	No
Lecturer	Michelle Simmons					No	No
Administrator	Zofia Krawczyk					No	No

Other Useful Information

Academic Information

Upon your enrolment at UNSW, you share responsibility with us for maintaining a safe, harmonious and tolerant University environment.

You are required to:

- Comply with the University’s conditions of enrolment.
- Act responsibly, ethically, safely and with integrity.
- Observe standards of equity and respect in dealing with every member of the UNSW community.
- Engage in lawful behaviour.

- Use and care for University resources in a responsible and appropriate manner.
- Maintain the University's reputation and good standing.

For more information, visit the UNSW Student Code of Conduct Website.

Academic Honesty and Plagarism

Referencing is a way of acknowledging the sources of information that you use to research your assignments. You need to provide a reference whenever you draw on someone else's words, ideas or research. Not referencing other people's work can constitute plagiarism.
Further information about referencing styles can be located at https://student.unsw.edu.au/referencing

Academic integrity is fundamental to success at university. Academic integrity can be defined as a commitment to six fundamental values in academic pursuits: honesty, trust, fairness, respect, responsibility and courage. At UNSW, this means that your work must be your own, and others' ideas should be appropriately acknowledged. If you don't follow these rules, plagiarism may be detected in your work.
Further information about academic integrity, plagiarism and the use of AI in assessments can be located at:

- The Current Students site,
- The ELISE training site, and
- The Use of AI for assessments site.

The Student Conduct and Integrity Unit provides further resources to assist you to understand your conduct obligations as a student: https://student.unsw.edu.au/conduct

Submission of Assessment Tasks

Penalty for Late Submissions

UNSW has a standard late submission penalty of:

- 5% per day,
- for all assessments where a penalty applies,
- capped at five days (120 hours) from the assessment deadline, after which a student cannot submit an assessment, and
- no permitted variation.

Any variations to the above will be explicitly stated in the Course Outline for a given course or assessment task.

Students are expected to manage their time to meet deadlines and to request extensions as early as possible before the deadline.

Special Consideration

If circumstances prevent you from attending/completing an assessment task, you must officially apply for special consideration, usually within 3 days of the sitting date/due date. You can apply by logging onto myUNSW and following the link in the My Student Profile Tab. Medical documentation or other documentation explaining your absence must be submitted with your application. Once your application has been assessed, you will be contacted via your student email address to be advised of the official outcome and any actions that need to be taken from there. For more information about special consideration, please visit: https://student.unsw.edu.au/special-consideration

Important note: UNSW has a “fit to sit/submit” rule, which means that if you sit an exam or submit a piece of assessment, you are declaring yourself fit to do so and cannot later apply for Special Consideration. This is to ensure that if you feel unwell or are faced with significant circumstances beyond your control that affect your ability to study, you do not sit an examination or submit an assessment that does not reflect your best performance. Instead, you should apply for Special Consideration as soon as you realise you are not well enough or are otherwise unable to sit or submit an assessment.

Faculty-specific Information

Additional support for students

- The Current Students Gateway
- Student Support
- Academic Skills and Support
- Student Wellbeing, Health and Safety
- Equitable Learning Services
- UNSW IT Service Centre
- Science EDI Student Initiatives, Offerings and Guidelines