University of London

MSci Intercollegiate Planning Board

Physics MSci
Student Handbook

Intercollegiate taught courses for 2009-2010 session

BPC 17th Sept 2009.

Contents

Courses and Teachers

Each course has a code number used by the Intercollegiate MSci board, shown at the left hand side. Colleges use local codes for the courses they teach. The *number* is usually the same as the MSci code, but some are different; beware! Local course codes are shown at the right hand side.

All courses are a half course unit (15 credits). In QMUL language, they are a full course unit.

The list shows the course title and the term in which it is taught. Also indicated is the course teacher and the college from where he/she comes.

No.	Course Title	Term	Teacher		Local no
4201	Math Methods for Theoretical Physics	1	Prof S. Sarkar	KCL	7CCP4201
4205	Lie Groups and Lie Algebras	1	Dr. I. Runkel	KCL	7CMMS01
4211	Statistical Mechanics	2	Prof. B. Cowan	RHUL	PH4211
4226	Advanced Quantum Theory	1	Dr. D. Brown	UCL	PHASM426
4242	Relativistic Waves & Quantum Fields	2	Dr. A. Brandhuber	QMUL	PHY415
4261	Electromagnetic Theory	1	Dr. S. Ramgoolam	QMUL	PHY966
4317	Galaxy and Cluster Dynamics	1	Prof. M. Cropper	UCL	PHASM317
4421	Atom and Photon Physics	1	Dr. C. Faria	UCL	PHASM421
4427	Quantum Computation and Communication	2	Prof. S. Bose	UCL	PHASM427
4431	Molecular Physics	2	Prof. A. Shluger	UCL	PHASM431
4442	Particle Physics	1	Prof. M. Lancaster	UCL	PHASM442
4450	Particle Accelerator Physics	1	Dr. P. Karataev	RHUL	PH4450
4472	Order and Excitations in Condensed Matter	2	Prof. D. McMorrow	UCL	PHASM472
4473	Theor. Treatments of Nano-systems	2	Dr. A. De Vita	KCL	7CP4473
4474	Physics at the Nanoscale	1	Prof. G. Davies & Prof. V. Petrashov	KCL	7CP4474
4478	Superfluids, Condensates and Superconductors	1	Prof. J. Saunders	RHUL	PH4478
4500	Standard Model Physics and Beyond	2	Prof. Mavromatos	KCL	7CCP4500
4512	Nuclear Magnetic Resonance	2	Prof. B. Cowan +	RHUL*	PH4512
4515	Computing and Statistical Data Analysis	1	Dr. G. Cowan	RHUL	PH4515
4534	String Theory and Branes	2	Dr. N. Lambert	KCL	7CMMS34
4541	Supersymmetry & Gauge Symmetry	2	Dr. N. Lambert	KCL	7CMMS41
4600	Stellar Structure and Evolution	2$	Prof. I. Williams	QMUL‡	MAS415
4601	Advanced Cosmology	1	Prof. J. Lidsey	QMUL‡	MAS401
4602	Relativity and Gravitation #	2	Dr. A. G. Polnarev	QMUL‡	MAS412
4603	Astrophysical Fluid Dynamics	2	Dr. S. Vorontsov	QMUL‡	MAS402
4630	Planetary Atmospheres	2	Prof. I. Mason	UCL	PHASM312

4640	Solar Physics	2	Dr. I. Phillips & Dr. van Driel	UCL	PHASM314
4650	Solar System	1$	Dr. J. R. Donnison	QMUL‡	MAS423
4660	The Galaxy	2$	Dr. J. R. Donnison	QMUL‡	MAS430
4670	Astrophysical Plasmas	1$	Prof. D. Burgess	QMUL‡	ASTM116
4680	Space Plasma and Magnetospheric Physics	2	Dr A. Coates & Dr C. Owen	UCL	PHASM465
4690	Extrasolar Planets & Astroph. Discs	2	Prof. R. Nelson	QMUL‡	MTH735U
4800	Molecular Biophysics	2	Dr. B. Hoogenboom	UCL	PHASM800

Students will undertake one or more project-related courses in accordance with practice at their own colleges.

‡ Courses taught by the *Mathematics* department of QMUL.
$ These QMUL courses taught in the *evening* this session.
* Courses taught at RHUL in Egham.
# Course unavailable to UCL students for syllabus reasons

Web and Email Addresses

You can communicate with most of the course teachers using email. And some courses have their own web pages. Address details are given in the following table.

No.	Course and web address	Teacher email address
4201	Math Methods for Theoretical Physics	
4205	Lie Groups and Lie Algebras	
4211	Statistical Mechanics http://personal.rhul.ac.uk/UHAP/027/PH4211/	b.cowan@rhul.ac.uk
4226	Advanced Quantum theory http://www.tampa.phys.ucl.ac.uk/%7Etania/QM4226.html	t.monteiro@theory.phys.ucl.ac.uk
4242	Relativistic Waves & Quantum Fields http://www.strings.ph.qmul.ac.uk/~andreas/RWQF/rwqf.html	a.brandhuber@qmul.ac.uk
4261	Electromagnetic Theory http://monopole.ph.qmul.ac.uk/~bill/EMHomePage.html	s.ramgoolam@qmul.ac.uk
4317	Galaxy and Cluster Dynamics	msc@mssl.ucl.ac.uk
4421	Atom and Photon Physics	w.r.newell@ucl.ac.uk
4427	Quantum Computation and Communication	s.bose@ucl.ac.uk
4431	Molecular Physics	a.bain@ucl.ac.uk
4442	Particle Physics http://www.hep.ucl.ac.uk/~markl/teaching/4442	markl@hep.ucl.ac.uk
4450	Particle Accelerator Physics	pavel.karataev@rhul.ac.uk
4472	Order & Excitations in Cond. Matt.	d.mcmorrow@ucl.ac.uk
4473	Theoretical Treatments of Nano-systems http://www.kcl.ac.uk/kis/schools/phys_eng/physics/courses/CourseList/CP4473.htm	Alessandro.de_vita@kcl.ac.uk
4474	Physics at the Nanoscale http://www.kcl.ac.uk/kis/schools/phys_eng/physics/courses/CourseList/CP4474.htm	gordon.davies@kcl.ac.uk v.petrashov@rhul.ac.uk
4478	Superfluids, Condensates and Superconductors	j.saunders@rhul.ac.uk
4500	Standard Model Physics and Beyond	
4512	Nuclear Magnetic Resonance	b.cowan@rhul.ac.uk
4515	Computing & Statist. Data Analysis http://www.pp.rhul.ac.uk/~cowan/stat_course.html	g.cowan@rhul.ac.uk
4534	String Theory and Branes	
4541	Supersymmetry and Gauge Symmetry	
4600	Stellar Structure and Evolution	I.P.Williams@qmul.ac.uk
4601	Advanced Cosmology www.maths.qmul.ac.uk/~jel/ASTM108/index.html	J.E.Lidsey@qmul.ac.uk
4602	Relativity and Gravitation http://www.maths.qmul.ac.uk/~agp/MAS412	A.G.Polnarev@qmul.ac.uk
4603	Astrophysicsl Fluid Dynamics www.maths.qmul.ac.uk/~svv	S.V.Vorontsov@qmul.ac.uk
4630	Planetary Atmospheres	imm@mssl.ucl.ac.uk
4640	Solar Physics http://www.mssl.ucl.ac.uk/~lvdg/	idp@mssl.ucl.ac.uk

4650	Solar System www.maths.qmul.ac.uk/~agnor/MAS423	R.Donnison@qmul.ac.uk
4660	The Galaxy www.maths.qmul.ac.uk/~jbj/teaching/msc-galaxy	R.Donnison@qmul.ac.uk
4670	Astrophysical Plasmas www.space-plasma.qmul.ac.uk/astroplasmas	D.Burgess@qmul.ac.uk
4680	Space Plasma and Magnetospheric Physics	ajc@mssl.ucl.ac.uk cjo@mssl.ucl.ac.uk
4690	Extrasolar Planets and Astrophysical Discs	R.P.Nelson@.ac.uk
4800	Molecular Biophysics	

Teaching and Examination Arrangements

Teaching Term Dates: Courses are taught in eleven-week terms. For the session 2009-2010 the teaching dates are:

First term

a) courses taught by UCL:
Monday 5th October 2009 – Friday 18th December 2009

b) course taught by QMUL, KCL and RHUL
Monday 28th September 2009 – Friday 11th December 2009

Second term Monday 11th January 2010 – Friday 26th March 2010

Note: these teaching dates may not be the same as your College terms!

Some courses – particularly Astro courses at QMUL might run according to the home college's term dates. You should check dates with the course leader.

Class locations
The timetable gives details of room locations; this is published separately from the Handbook and it is also available on the Intercollegiate MSci web pages.

Most courses are taught in lecture rooms at UCL. The exceptions are:

Courses taught at KCL

4201 Math Methods for Theoretical Physics
4205 Lie Groups and Lie Algebras
4500 Standard Model Physics and Beyond
4534 String Theory and Branes
4541 Supersymmetry & Gauge Symmetry

Courses taught at QMUL

4600 Stellar Structure and Evolution
4601 Advanced Cosmology
4602 Relativity and Gravitation
4603 Astrophysical Fluid Dynamics
4650 Solar System
4660 The Galaxy
4670 Astrophysical Plasmas

Some of these courses will be taught in the evening; check page 3 and the timetable for details.

Courses taught at RHUL – central London base

4211 Statistical Mechanics

Courses taught at RHUL – Egham campus

4512 Nuclear Magnetic Resonance

Coursework policy
Some courses have coursework associated with them and others do not. The details are given in the Course Descriptions below. Note that for courses taught by UCL *you must achieve an overall coursework mark of at least 15% otherwise you will fail that course*.

Examination arrangements
UCL Students: You will sit UCL and RHUL examinations at UCL. You will sit KCL examinations at KCL and QMUL examinations at QMUL.

KCL Students: You will sit KCL and RHUL examinations at KCL. You will sit UCL examinations at UCL and QMUL examinations at QMUL.

QMUL Students: You will sit QMUL and RHUL examinations at QMUL. You will sit UCL examinations at UCL and KCL examinations at KCL.

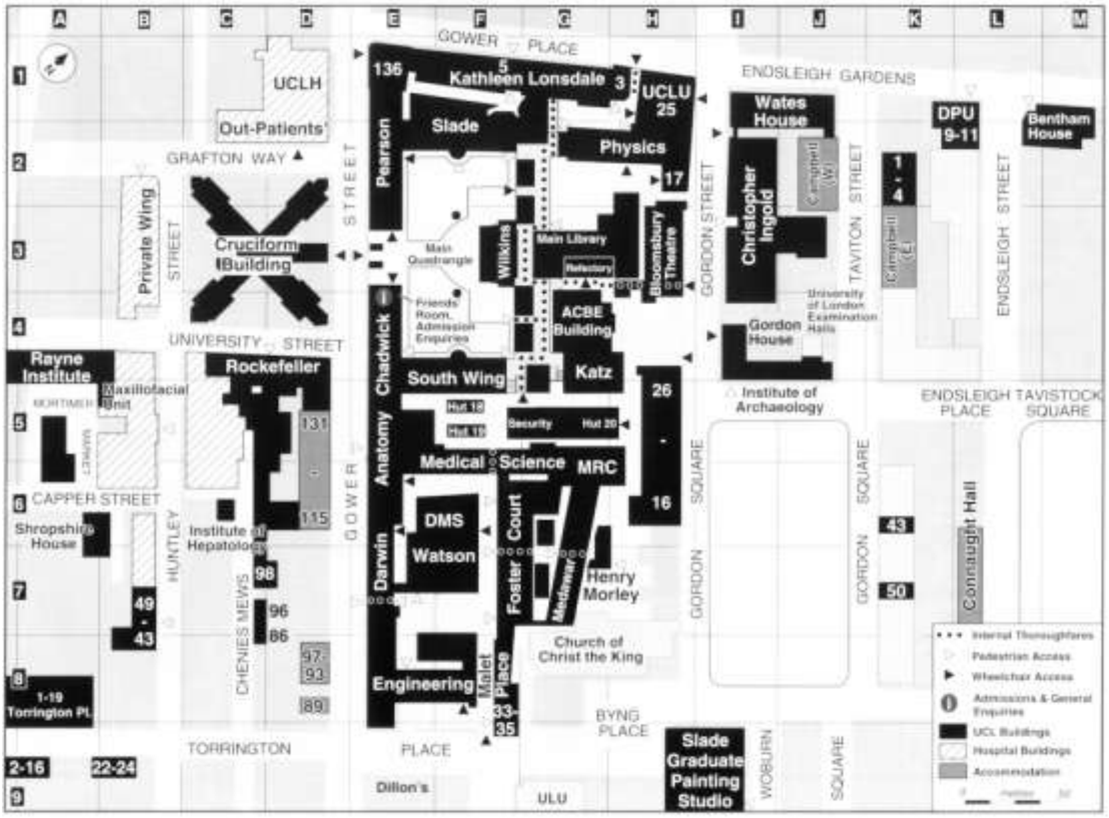
RHUL students: You will sit all your examinations at RHUL.

Computer and Library facilities at UCL
Students taking UCL modules may be given temporary computer accounts at UCL; your College MSci coordinator will be able to make the arrangements for you.

Most of the fourth year lectures take place in UCL lecture rooms. While you are there you might want to make use of the UCL library facilities. Your College MSci coordinator will be able to make the arrangements for you to do this.

College and Class Locations

University College, Gower Street, London WC1.



Room A1, Top Floor, Physics and Astronomy building.
Through the Gower Place gateway, up steps to the second building on the left. Follow the corridor round to lift.

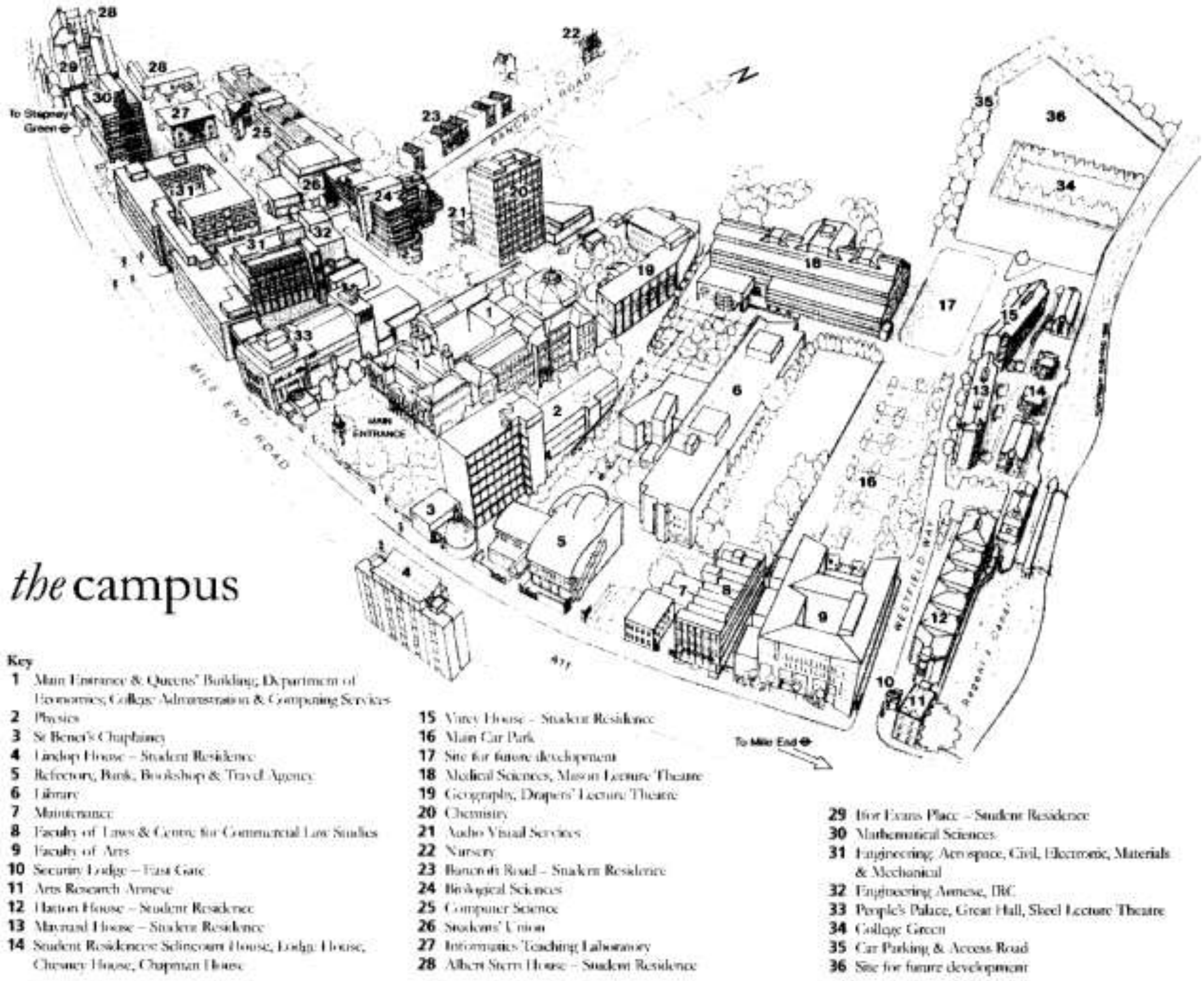
Room A19, Top Floor, Physics and Astronomy building.
Through the Gower Place gateway, up steps to the second building on the left. Follow the corridor round to lift.

Room D103, First Floor, 25 Gordon Street (Maths/Union building).
This is in the north-east corner of the UCL rectangle, at the corner of Gordon Street and Gower Place. It is most easily approached through the gateway in Gower Place, taking the first entrance on the left.

Remax 2.02: Remax House, UCL, Alfred Place, Chenies Street. This is not on the above map. Go down Gower St. past Torrington Place. Take the next right turn into Chenies Street and the first left turn into Alfred Place.

Room 500, Mathematics department, in Student Union building, 25 Gordon Street (beside physics).

Queen Mary University of London, Mile end Road, London E1. From Stepney Green station, turn left. Students may obtain a campus map from the Physics Department Secretarial office on the second floor of the Physics Building in Rooms 210 or 211.

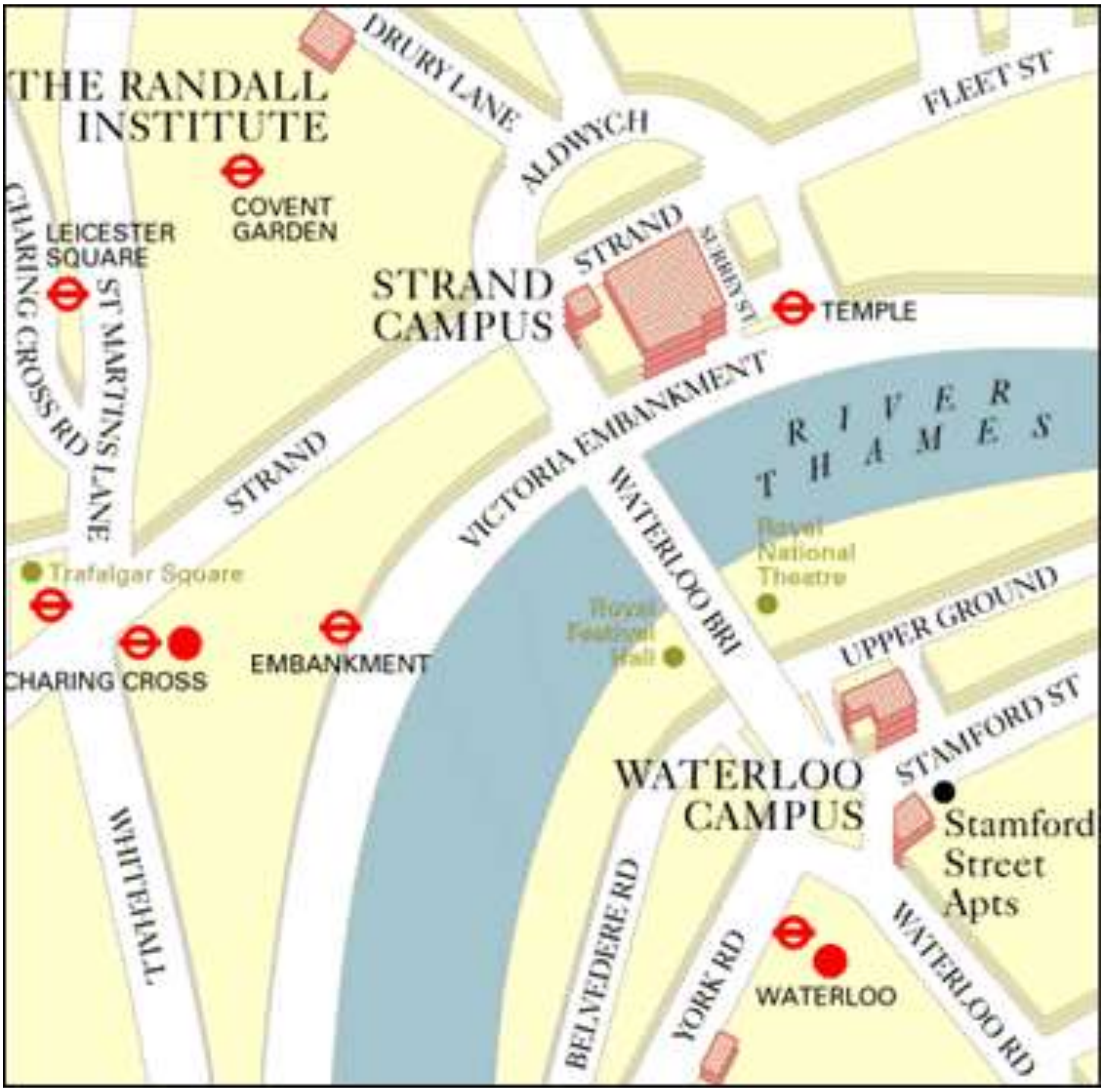


Physics 112 – first floor of Physics Building (2) that is beside the Queens Building (1) as one enters the main College entrance on the Mile End Road.
Physics PLG1 – this is in the basement of the Physics Building (2). Enter the Physics Building, go straight past the lifts to the main stairwell, descend one flight and follow the corridor to the end of the building where the Lecture room entrance may be found.

Mathematics 103 – Mathematics building (30) at West end of campus, entered from the Mile End Road. M103 is on the first floor; this room is also called the Maths Seminar Room.

Engineering 306 – in Engineering Building (31), which is on the Mile End Road between the main entrance to the College and the Mathematics Building (30) – entrance from Mile End Road beside the People's Palace (33). Take the lift or stairs to the 3rd floor and then pass through the Materials Department corridor past 304 and 305 to 306 which is just at a short right –left turn in this corridor.

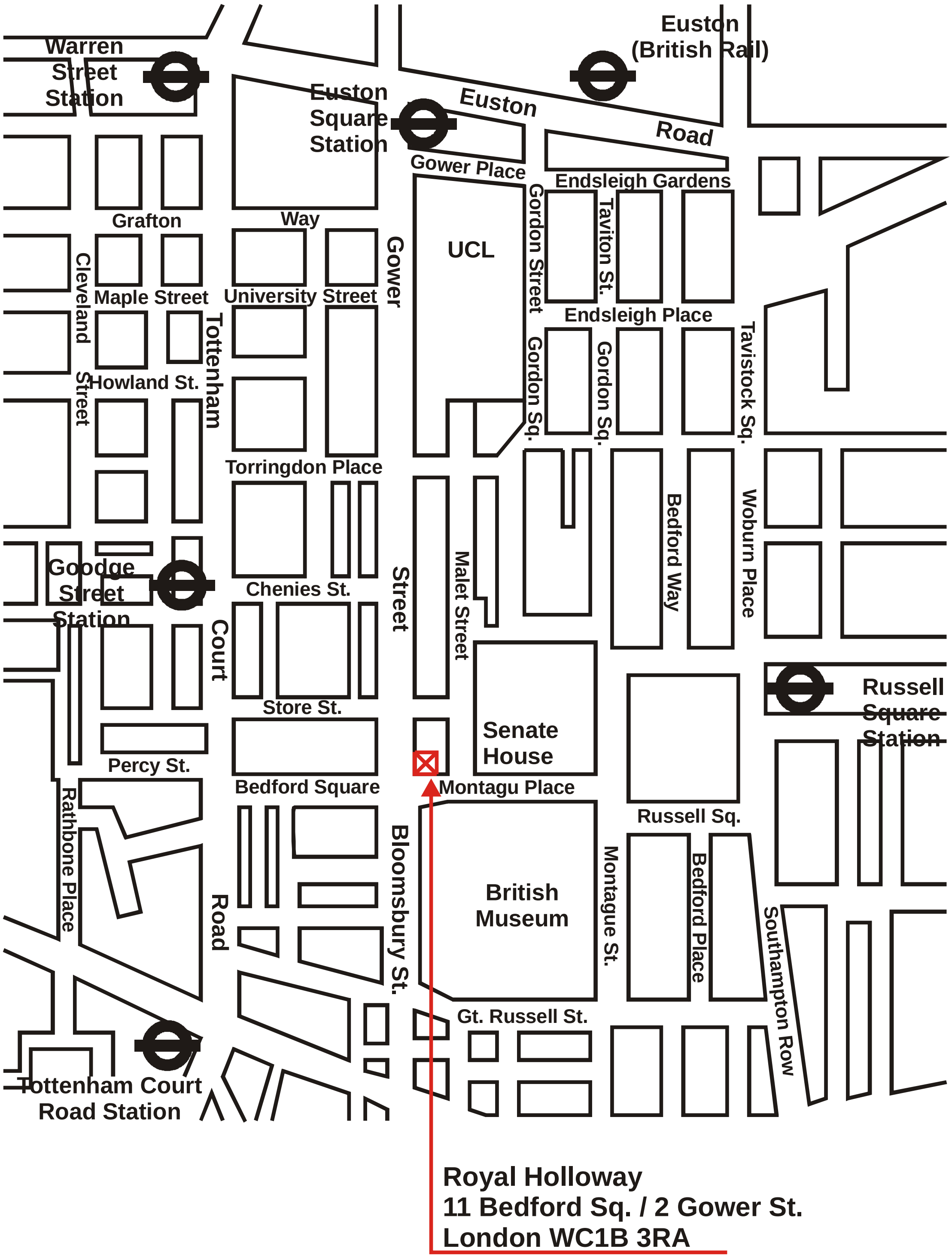
King's College, Strand. London, WC2.



Room 25C, Physics/Computer Project Laboratory: 2nd floor, Main (Old) Building. Enter the main lobby from the Strand. Take the lift to the second floor. From the lift turn right and immediately right again into the 'C' corridor of the main building (signposted). When in the main building the Physics Laboratory area is signposted as the 3rd door on the left. From this entrance area take the wooden stairs up one floor to Room 25C.

Room Q135, below the main quadrangle. From the main door, turn left and go down stairs to the Physics Department.

Royal Holloway University of London, central London base. **11 Bedford Square and 2 Gower Street**. These are two adjacent buildings on the corner of Bedford Square and Gower Street.



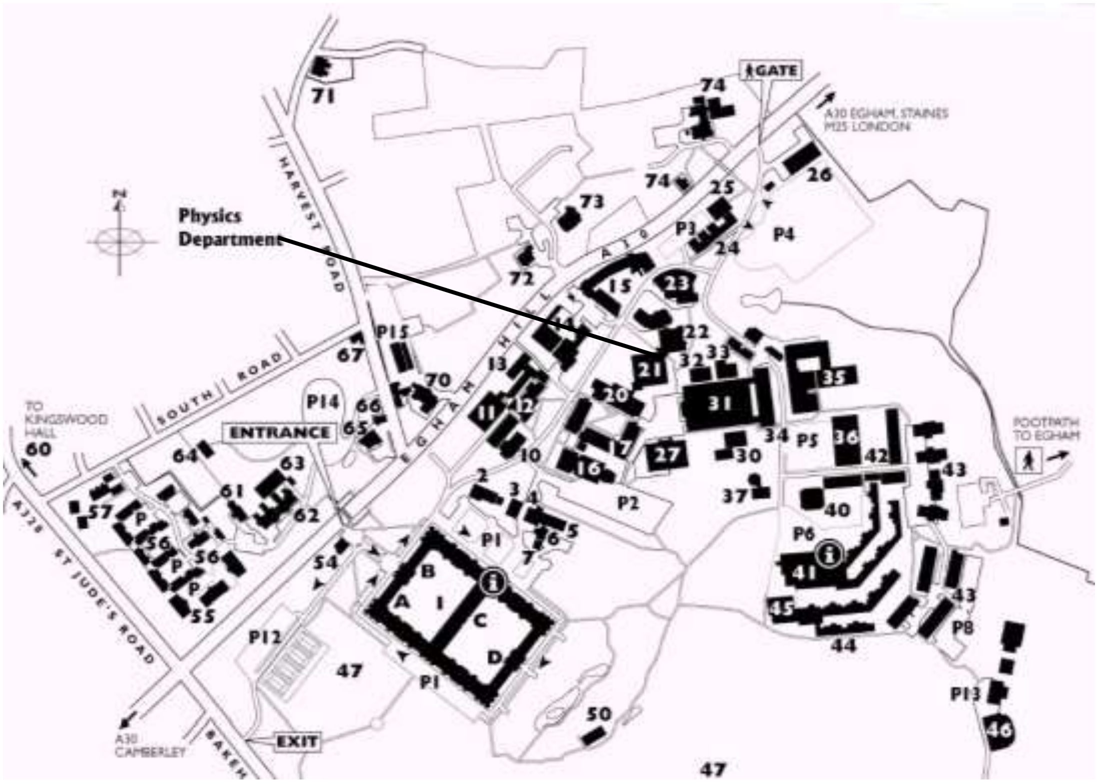
On arrival students must sign in at the front desk of the Bedford Square building before proceeding to their class. The Gower Street building is kept locked; the course teacher will obtain the key to the front door and students may need to ring the bell to gain entrance.

Royal Holloway University of London, Egham campus

By Road: The College is on the A30, 20 miles from central London and about a mile south-west of the town of Egham. It is 2 miles from junction 13 of the M25 (London Orbital). After leaving the motorway take the A30 west, signposted to Bagshot and Camberley (not Egham). At the first roundabout, take the second exit; at the second roundabout, again take the second exit and continue on the A30 up Egham Hill. The College is on the left at the top of the hill. There are footbridges across the road at the pedestrian and main entrances.

By Rail: There are frequent services from London Waterloo to Egham (35 minutes); Woking to Egham (35 minutes, change at Weybridge) and Reading to Egham (40 minutes). Services at weekends, especially those on Sunday, are less frequent than on weekdays.

By Foot: The College is just over a mile from Egham Station, about 20 minutes walk. Turn right out of the station along Station road and walk about 100 yards to the T-Junction and the traffic lights. Turn left at the junction and follow the road up to the large roundabout; go left up Egham Hill (south-west direction). It is easiest to enter by the gate before the foot bridge over the road and follow the path to the Physics Department – buildings 21 and 22.



4201 Mathematical Methods for Theoretical Physics

Aims and Objectives

This course introduces mathematical techniques which are crucial to the formulation and solution of fundamental theories in Physics. It is biased towards the application of mathematics to solve problems, rather than the development of rigorous mathematics. It assumes competence in the use of mathematics covered in previous mathematical courses given in the first and second years,. On finishing the course, students should be able to solve physics problems through complex analysis, the calculus of variations, and extend the definition of special functions to the complex plane.

Syllabus outline

Functions of a complex variable: limits, continuous and differentiable functions; Cauchy-Riemann equations for an analytic function $f(z)$; physical significance of analytic functions; properties of power series, definition of elementary functions using power series; complex integral calculus, contour integrals, upper bound theorem for contour integrals; Cauchy-Goursat theorem; Cauchy integral representation, Taylor and Laurent series, singularities and residues; residue theorem and its applications. Properties of the gamma function $\Gamma(z)$. Bessel functions; series solution of the Bessel differential equation; definition of $J_n(z)$ and $Y_n(z)$; recurrence relations for $J_n(z)$; zeros of $J_n(z)$; orthogonality properties of Bessel functions; solution of the wave equation in plane polar coordinates. Classical mechanics; constraints and generalised co-ordinates; D'Alembert's principle; Lagrange equations of motion; conservation laws; Hamilton's equation of motion; conservation laws and Poisson brackets. Calculus of variation; method of Lagrange multipliers; functionals; Euler-Lagrange equation; minimum surface energy of revolution; properties of soap films; Hamilton's principle in classical dynamics; multiple integral problems and field equations.

4205 Lie Groups and Lie Algebras

Aims and objectives:
This course gives an introduction to the theory of Lie groups, Lie algebras and their representations. Lie groups are essentially groups consisting of matrices satisfying certain conditions (e.g. that the matrices should be invertible, or unitary, or orthogonal). They arise in many parts of mathematics and physics. One of the beauties of the subject is the way that methods from many different areas of mathematics (algebra, geometry, analysis) are all brought in at the same time. The course should enable you to go on to further topics in group theory, differential geometry, string theory and other areas.

Syllabus:
Examples of Lie groups and Lie algebras in physics. Matrix Lie groups, matrix Lie algebras, the exponential map, BCH formula. Abstract Lie algebras, examples: sl(2), sl(3), Poincare algebra. Representations of Lie algebras, sub-representations, Schur's Lemma, tensor products. Cartan-Weyl basis, classification of simple Lie algebras (without proof).

Web page: See http://www.mth.kcl.ac.uk/courses

Teaching arrangements:
Two hours of lectures per week

Prerequisites:
Basic knowledge of vector spaces, matrices, groups, real analysis.

Assessment:
One two-hour written examination at the end of the academic year.
Assignments:
Exercises in the course notes. Solutions will be provided.

Books:
There is no book that covers all the material in the same way as the course, but the following may be useful:

- Baker, Matrix groups, Springer, 2002
- J. Fuchs, C. Schweigert, Symmetries, Lie algebras and representations, CUP 1997
- J. Humphreys, Introduction to Lie Algebras and Representation Theory, Springer, 1972
- H. Jones, Groups, Representations and Physics, IoP, 1998

4211 Statistical Mechanics

The Methodology of Statistical Mechanics (5 lectures)

- Review of equilibrium statistical mechanics.
- The grand canonical ensemble. Chemical potential. The Bose and Fermi distribution functions.
- The classical limit, phase space, classical partition functions.

Weakly Interacting Systems (7 lectures)

- Non-ideal systems. The imperfect gas and the virial expansion, Mayer's f function and cluster integrals. (2 lectures)
- The second virial coefficient for the hard sphere, square-well and Lennard-Jones potentials. (2 lectures)
- Throttling and the Joule-Kelvin coefficient. (1 lecture)
- Details of the van der Waals gas and the mean field theory for magnetic systems. (2 lectures)

Strongly Interacting Systems (13 lectures)

- The phenomenology of phase transitions, definitions of critical exponents and critical amplitudes. (2 lectures)
- Scaling theory, corresponding states. (2 lectures)
- Introduction to the Ising model. Magnetic case, lattice gas and phase separation in alloys and Bragg-Williams approximation. Transfer matrix method in 1D. (3 lectures)
- Landau theory. Symmetry breaking. Distinction between second order and first order transitions. Discussion of ferroelectrics. (3 lectures)
- Broken symmetry, Goldstone bosons, fluctuations, scattering, Ornstein Zernike, soft modes. (3 lectures)

Dissipative Systems (5 lectures)

- Fluctuation-dissipation theorem, Brownian motion, Langevin equation, correlation functions. (5 lectures)

Books:
B. Cowan, "Topics in Statistical Mechanics", 2005, Imperial College Press.
R. Bowley & M. Sánchez, "Introductory Statistical Mechanics", 1999, OUP
Other books and publications will be referred to by the lecturer.
Course notes and other material available on the course web pages at
http://personal.rhul.ac.uk/UHAP/027/PH4211/

Assessment:
Written examination of 2½ hours contributing 90%, coursework contributing 10%.

4226 Advanced Quantum Theory

The module consists of 30 lectures. These will be used to cover the syllabus material and to discuss problem sheets as the need arises. The approximate allocation of lectures to topics is shown in brackets below.

Basic ideas of quantum mechanics (partly revision) and formal quantum mechanics[5]
(Formal aspects of quantum theory are distributed throughout the course and introduced as needed.)
Bras and kets, states, operators, Born interpretation of the wave function, continuous and discrete eigenvalues, Dirac delta function, compatible observables, Hermitian and unitary operators, Dirac notation, closure relation, time-evolution, Schrödinger, Heisenberg and interaction pictures, transformation brackets, momentum representation.

Angular momentum (partly revision) [5]
Angular momentum operators, commutation algebra, raising and lowering operators, spectrum of angular momentum eigenvalues, combination of angular momenta treating the simplest case of two spin-1/2 particles, notation of Clebsch-Gordan coefficients, spin-1/2 angular momentum and Pauli matrices.

Non-perturbative approximations [4]
The JWKB approximation. Examples.

Time-dependent perturbation theory [7]
First-order time-dependent perturbation theory. Harmonic perturbations and other applications of time-dependent perturbation theory. Second-order perturbation theory and energy denominators. First Born approximation from the dependent approach. Fermi's Golden Rule.

Scattering [9]
Currents and cross sections; the scattering amplitude and the optical theorem. Partial wave expansion of wave function and scattering amplitude. Phase shifts. Low-energy scattering from square well potential and scattering length expansion. Scattering length expansion in terms of wave functions. Poles of the scattering amplitude, bound states and resonances. First Born approximation from the time-independent approach. Integral equation for potential scattering.

Books:
Those which are closest to the material and level of the course are (in alphabetical order)

- *Introduction to Quantum Mechanics*, B.H. Bransden and C.J.Joachain, Longman (2^{nd} Ed, 2000),) (available at a discount from the physics departmental Tutor),
- *Quantum Mechanics*, (2 Vols) C.Cohen-Tannoudji, B.Diu and F.Laloe, Wiley,
- *Quantum Physics*, S.Gasiorowicz, Wiley (1996),
- *Quantum Mechanics*, F.Mandl , Wiley (1992),
- *Quantum Mechanics*, E.Merzbacher, (3rd Ed.) Wiley, (1998

Assessment: Examination of 2½ hours duration contributing 90%, coursework 10%.

Prerequisites:
The following topics will be assumed to have been covered:

Introductory material: states, operators and the Born interpretation of the wave function, transmission and reflection coefficients;
Harmonic oscillator: by the differential equation approach giving the energy eigenvalues and wave functions;
Angular momentum: angular momentum operators and the spectrum of eigenvalues, raising and lowering operators; the spherical harmonics and hydrogenic wave functions;
Time-independent perturbation theory: including the non-degenerate and degenerate cases and its application to the helium atom ground state, Zeeman effect and spin-orbit interactions.

Aims of the Course
This course aims to:
- review the basics of quantum mechanics so as to establish a common body of knowledge for the students from the different Colleges on the Intercollegiate M.Sci. programme;
- extend this by discussing these basics in more formal mathematical terms;
- develop the JWKB method for non-perturbative approximations;
- discuss the addition of angular momentum and Clebsch-Gordan coefficients;
- introduce time-dependent perturbation theory ;
- discuss the quantum mechanical description of the non-relativistic potential scattering of spinless particles in terms of the partial wave expansion and the Born approximation;
- provide the students with basic techniques in these areas which they can then apply in specialist physics courses.

4242 Relativistic Waves and Quantum Fields

Quantum Mechanics and Special Relativity (part revison): (6 hours)
Schroedinger equation, wavefunctions, operators/observables, pictures, symmetries and conservation laws in QM; short introduction to Special Relativity: 4-vector notation, Lorentz transformations, Lorentz invariance/covariance, Lorentz transformation of the electromagnetic field

Relativistic Wave equations: (10 hours)
Klein-Gordon equation and probability density; Dirac equation, covariance and probability density, non-relativistic limit, spin, Feynman notation, plane wave solutions, Lorentz transformations of plane wave solutions; hole theory and anti-particles, vacuum polarisation; discrete symmetries: C & P & T symmetry and their relevance for electromagnetic and weak interactions, Dirac covariants; wave equations for massless fermions, neutrinos; Feynman interpretation of the Klein-Gordon equation; Dirac equation in an electromagnetic field, magnetic moment of electron, relativistic spectrum of Hydrogen atom.

Quantum Field Theory: (17 hours)
Classical field theory, Noether theorem, stress-energy tensor, symmetries and conserved currents; canonical quantisation of the Klein-Gordon field, creation and annihilation operators, vacuum energy, Casimir energy; quantisation of Dirac fermion, spin- statistics connection; commutators and time ordered products, the Feynman propagator; Dyson expansion; S–matrix, scattering amplitudes, transition rates; cross sections; Φ^4–theory scattering amplitude; decay rates of unstable particles; Wick's theorem and its application to perturbation theory, Feynman rules; quantisation of electromagnetic field and Gupta-Bleuler formalism; interaction with electron; Feynman rules & various scattering processes: Compton, electron-electron, electron-positron; cross sections and spin sums.

Four sessions will be devoted to a discussion of coursework problems and their solutions.

Prerequisites: 3rd year Quantum course

Books:
F. Mandl and G. Shaw, "Quantum Field Theory", John Wiley and Sons Ltd
L.H. Ryder, "Quantum Field Theory", Cambridge University Press
J. Bjorken and S. Drell, "Relativistic quantum mechanics" and "Relativistic quantum fields", McGraw-Hill
S. Weinberg, "The Quantum Theory of Fields", Volume I, Cambridge University Press

Assessment:
Written examination of 2½ hours contributing 90%, coursework contributing 10%.

4261 Electromagnetic Theory

- Revision of laws of electromagnetism *in vacuo*, displacement current, Maxwell's equations *in vacuo*, charge and current density sources, energy theorems, fluxes of energy and momentum. (2 hours)

- Polarization and magnetization, **D** and **H** fields, linear media, boundary conditions on the fields in media, Maxwell stress tensor, concept of macroscopic fields as space averages of molecular fields, Lorentz local field argument, the Clausius-Mossotti relation. (3 hours)

- Maxwell's equations in media, Homogeneous wave equation *in vacuo* and in media, concept of frequency dependent dielectric function $\varepsilon(\omega)$, properties of real and imaginary parts of $\varepsilon(\omega)$, causality, Kramers-Krönig relation. (3 hours)

- Scalar and vector potentials, gauge transformations, inhomogeneous wave equation, the retarded solution to the wave equation, radiation from a Hertzian dipole with discussion of near and far fields, formula for power radiated, qualitative discussion of magnetic dipole and electric quadrupole radiation. (4 hours)

- Scattering of a plane wave by a single slowly moving charged particle, total and differential scattering cross-sections, optical theorem, scattering from a medium with space-varying dielectric constant, scattering from an assemblage of polarizable particles, Rayleigh-Smoluchowski-Einstein theory of why the sky is blue – critical opalescence. (5 hours)

- Lorentz transformations, charge and current density as a 4-vector, the potential 4-vector, tensors and invariants, the relativistic field tensor $F^{\mu\nu}$, Lorentz transformation properties of current density and potential 4-vectors and of the free vacuum **E** and **B** fields, tensor form of Maxwell's equations, covariant formulation of energy and momentum theorems, energy-momentum tensor. (5 hours)

- Liénard-Wiechert potentials for a moving charged particle derived from a delta-function source, fields for a uniformly moving charged particle in the non-relativistic and ultra-relativistic limits, radiation from accelerated charges, the cases of velocity and acceleration parallel and perpendicular, Larmor formula for radiated power, bremsstrahlung and synchrotron radiation as examples. (5 hours)

- Maxwell theory as a Lagrangian field theory, the free field as an ensemble of oscillators. (3 hours)

Prerequisites:
The course assumes a knowledge of the electromagnetism topics as detailed in the Institute of Physics Recommended Core. These comprise:

- Electrostatics: the electric field **E**
- Charge. Coulomb's law, Gauss's flux theorem
- Electrostatic potential; Poisson's and Laplace's equations
- The field and potential of a point charge and an electric dipole
- Capacitance and stored energy
- Magnetostatics: the magnetic field **B**
- Electric currents; the Biot-Savart law, Ampère's circuital theorem
- The field of a linear current and of a magnetic dipole/current loop
- Lorentz force law, force on current-carrying conductors
- Motion of particles in electric and magnetic fields
- Electrodynamics: Faraday's law, Lenz's law and induction
- Inductance and stored magnetic energy
- Maxwell's equations and electromagnetic waves
- The electromagnetic spectrum
- The Poynting vector
- Fields in media: **D** and **H**; permittivity, permeability and dielectric constant: basic ideas, related to their microscopic origins
- Energy storage in media

In addition the following knowledge in mathematics and physics are assumed:

- Taylor series.
- Div, Grad and Curl, Surface and Volume integrals, Gauss and Stokes theorems.
- The complex representation of harmonically varying quantities.
- Fourier transforms.
- The one-dimensional wave equation.
- Matrix multiplication and familiarity with indices.
- Contour integration up to Cauchy's theorem (this is used only in the discussion of the Kramers-Krönig relation)
- From special relativity the explicit form of the simple Lorentz transformation between frames in relative motion along a single coordinate direction.
- It is desirable but not necessary that students have met the Lagrangian formulation of particle mechanics.
- We do not assume that students have met the concept of Green's functions before.

Books:
J D Jackson, "Classical Electrodynamics", J Wiley
H C Ohanian, "Classical Electrodynamics", Allyn and Bacon

Assessment:
Written examination of 2½ hours contributing 90%, coursework contributing 10%.

4317 Galaxy and Cluster Dynamics

Galaxies, Clusters and the Foundations of Stellar Dynamics [5]
Observational overview of extragalactic astronomy The classification of galaxies, star clusters, clusters of galaxies Characteristics of the Milky Way and other galaxies The uses of stellar dynamics. The equations of motion and the Collisionless Boltzmann Equation. Isolating integrals and Jeans' theorem

The Structure of the Milky Way [8]
Galactic co-ordinates, the local standard of rest and rotation curves. Differential rotation, Oort's constants, epicyclic motions. Motions perpendicular to the galactic plane. The third integral - 'box' and 'tube' orbits. Local galactic dynamics; star-streaming, Jeans' equations. Asymmetric drift. The gravitational field of the Milky Way. The growth of instabilities, spiral structure, the density wave theory

Stellar Encounters and Galactic Evolution [4]
The effects of distant stellar encounters, two-body relaxation. The Fokker-Planck approximation, dynamical friction. The virial theorem and its applications

Star Clusters [5]
The dynamics of clusters; evaporation, the King model. The effects of tidal forces. Dynamical evolution and core collapse

Elliptical Galaxies [4]
Collisionless relaxation: phase damping and violent relaxation. Shapes and intensity profiles. Dynamical models; orbit families. Mergers and the origin of elliptical galaxies

Clusters of Galaxies [4]
The description of clustering, the Local Group. Dynamics of clusters of galaxies, formation timescales. The determination of galactic masses. The missing mass problem.

Books: Stellar Dynamics (I.R. King, W.H. Freeman, 1996)
Galaxies: Structure and Evolution (R.J. Tayler, Cambridge Univ. Press, 1993)

Assessment: Examination of 2½ hours duration contributing 90%, coursework 10%.

Prerequisite: UCL's ASTR3C36 - Cosmology and Extragalactic Astronomy or equivalent.

4421 Atom and Photon Physics

Interaction of Light with atoms (single photon) (4 lectures)
1 Processes – excitation, ionization, auto-ionization
2 A and B coefficients (semi classical treatment)
3 Oscillator strengths and *f*-sum rule
4 Life times – experimental methods. (TOF and pulsed electron)
5 Review of selection rules
6. Photo-ionization – synchrotron radiation

L.A.S.E.R (3 lectures)
1 Line shapes $g(\nu)$; Pressure, Doppler, Natural
2 Absorption and Amplification of radiation
3 Population inversion; spontaneous and stimultated emission
4 YAG and Argon ion lasers
5 Tunable radiation – dye and solid
6 Mode structure

Chaotic Light and Coherence (2 lectures)
1 Line broadening
2. Intensity fluctuations of chaotic light
3 First order correlation functions
4. Hanbury Brown Twiss experiment

Laser Spectroscopy (3 lectures)
1 Optical pumping – orientation and alignment
2 Saturation absorption spectroscopy
3 Lamb shift of H(1S) and H(2S)
4 Doppler-Free spectroscopy

Multi-Photon Processes (3 lectures)
1 Excitation, ionization, ATI
2 Laser field effects – pondermotive potential – Stark shifts – Harmonic Generation
3 Pump and Probe Spectroscopy
4 Multi-photon interactions via virtual and real states
5 Two photon decay of hydrogen (2S–1S)
6 Simultaneous electron photon interactions

Light Scattering by Atoms (3 lectures)
1 Classical Theory
2 Thompson and Compton scattering
3 Kramers-Heisenberg Forumlae
4 (Rayleigh and Raman scattering)

Electron Scattering by Atoms (4 Lectures)
1 Elastic, inelastic and super-elastic
2 Potential scattering
3 Scattering amplitude – partial waves

4 Ramsauer-Townsend Effect – Cross Sections
5 Resonance Structure

Coherence and Cavity Effects in Atoms (4 lectures)
1 Quantum beats – beam foil spectroscopy
2 Wave packet evolution in Rydberg states
3 Atomic decay in cavity
4. Single atom Maser

Trapping and Cooling (4 lectures)
1 Laser cooling of atoms
2 Trapping of atoms
3 Bose condensation
4 Physics of cold atoms – Atomic Interferometry

Books:
A Thorne, “Spectrophysics”, (Chapman and Hall)
J Wilson and J F B Hawkes, “Opto Electronics”, (Prentice Hall)

Assessment: Examination of 2½ hours duration contributing 90%, coursework 10%.

4427 Quantum Computation and Communication

Background [3]: The qubit and its physical realization; Single qubit operations and measurements; The Deutsch algorithm; Quantum no-cloning.

Quantum Cryptography [3]: The BB84 quantum key distribution protocol; elementary discussion of security; physical implementations of kilometers.

Quantum Entanglement [8]: State space of two qubits; Entangled states; Bell's inequality; Entanglement based cryptography; Quantum Dense Coding; Quantum Teleportation; Entanglement Swapping; Polarization entangled photons & implementations; von-Neumann entropy; Quantification of pure state entanglement.

Quantum Computation [8]: Tensor product structure of the state space of many qubits; Discussion of the power of quantum computers; The Deutsch-Jozsa algorithm; Quantum simulations; Quantum logic gates and circuits; Universal quantum gates; Quantum Fourier Transform; Phase Estimation; Shor's algorithm; Grover's algorithm.

Decoherence & Quantum Error Correction [4]: Decoherence; Errors in quantum computation & communication; Quantum error correcting codes; Elementary discussion of entanglement concentration & distillation.

Physical Realization of Quantum Computers [4]: Ion trap quantum computers; Solid state implementations (Kane proposal as an example); NMR quantum computer.

Books:

Assessment: Examination of 2½ hours duration contributing 90%, coursework 10%.

Prerequisites: Third year level quantum mechanics.

4431 Molecular Physics

1. Atomic Physics (2 lectures)
Brief recap of atomic physics: *n, l, m, s*; He atom, orbital approximation, exchange.

2. Molecular electronic structure (8 lectures):
The molecular Hamiltonian and the Born-Oppenheimer approximation.
Electronic structure, ionic and covalent bonding, Bonding in H_2^+ and H_2. Muon catalysed fusion. Dissociation and united atom limits. Long range forces.

3. Nuclear motion (6 lectures)
Vibrational structure: harmonic motion and beyond, energy levels and wavefunctions Rotational structure: rigid rotor and energy levels Energy scales within a molecule: ionisation and dissociation. Nuclear spin effects. Labeling schemes for electronic, vibrational and rotational states.

4. Molecular spectra (7 lectures):
Microwave, infrared and optical spectra of molecules. Selection rules, Franck-Condon principle. Experimental set-ups. Examples: the CO_2 laser, stimulated emission pumping experiment. Raman spectroscopy. Ortho-para states. Absorption spectra of simple diatomics (eg O_2 and NO, N_2). Simple poly-atomics (ozone, water).

5. Molecular processes (7 lectures):
Collisions with electrons. Elastic and inelastic collisions. Dissociation, dissociative attachment and dissociative recombination. Resonances and negative ions. Experimental techniques. Theoretical models (briefly).

Prerequisites: Quantum Physics (year 2/3), Atomic Physics (year 2/3), some previous experience of basic molecular physics would be helpful but is not a requirement.

Books:
P W Atkins and R S Friedman, "Molecular Quantum Mechanics", (Oxford University)
B H Bransden and C J Joachain, "Physics of Atoms and Molecules", (Longman, 1983)
C.W. Banwell and E. McGrath, "Fundamentals of Molecular Spectroscopy", 4th Edition, (McGraw-Hill, 1994)

Assessment:
Examination of 2½ hours duration contributing 90%, coursework 10%.

4442 Particle Physics

Basic Concepts
Four vector notation, invariants and natural units. Feynman diagrams as a tool for qualitative description of interactions. Cross sections, differential cross sections and luminosity. The Mandelstam variables s, t and u for scattering. The family of fundamental particles: leptons and quarks and vector bosons. Interactions of leptons and quarks, summarised in terms of characteristic decay times, ranges and the mediating bosons. Yukawa field.

Relativistic QM
Relativistic wave equations (Klein-Gordon, Dirac). Negative energy solutions and the Feynmann-Stuckelberg interpretation. Conserved Current and Propagators. Invariant amplitude.

Symmetries and conservation laws.
Translational invariance and momentum conservation as a worked example. Symmetries of the Strong and Electromagnetic Interactions: Relation between symmetry, invariance and conservation laws; parity (invariance of Hamiltonian, fermions and antifermions, quarks and hadrons). Higgs mechanism and spontaneous symmetry breaking.

Particle Detectors
These will be covered as an integral part of the study of current experiements. Basic principles of calorimeters, drift chambers and silicon vertex detectors.

Leptons and Hadrons
Discovery of leptons. Evidence for lepton universality, lepton number conservation. Parity, C Symmetry. Quarks, and hadrons. Multiplets and Quark diagrams. Resonances. Breit-Wigner formula.

Quarks and QCD
Colour. Confinement. Screening, Asymptotic freedom and Jets. Rhad for e^+e^- annihilation. 2- and 3-jet events. The discovery of the top quark through the measurement of jets at the CDF detector at Fermilab, including a look at basic calorimetry.

More on Leptons, and Weak Interactions
Discovery and properties of W and Z bosons. Quark and lepton doublets and Cabibbo mixing. Comparing the weak and electromagnetic couplings. Parity and C-Parity violation and handedness of neutrinos. The measurement of Z width at LEP. Electroweak Theory: Unification of weak and electromagnetic. Gauge transformations.

Deep Inelastic Scattering
Elastic electron-proton scattering. Deep Inelastic scattering. Scaling and the quark parton model. Factorisation. Scaling violations and QCD. Triggering at HERA. Measurement of proton structure at HERA. Neutral and Charged Currents at HERA.

The Standard Model and What Next?
Some idea of current open questions. Neutrino oscillations, running couplings, SUSY. Cosmological connections – dark matter, CP violation, very high energy cosmic rays.

Prerequisites: 4241 Relativistic Quantum Mechanics, Atomic and Nuclear (year 2/3)

Books:
B R Martin and G Shaw, "Particle Physics", J. Wiley
Halzen and Martin, "Quarks and Leptons", J. Wiley
D H Perkins, "Introduction to High Energy Physics", Addison-Wesley.

Assessment:
Examination of 2½ hours duration contributing 90%, coursework 10%.

4450 Particle Accelerator Physics

- Introduction: history of accelerators, basic principles including centre of mass energy, luminosity, accelerating gradient.
- Characteristics of modern colliders; LEP, LHC, b-factories.
- Transverse motion, principles of beam cooling.
- Strong focusing, simple lattices.
- Circulating beams, synchrotron radiation.
- Longitudinal dynamics.
- Multipoles, non-linearities and resonances.
- Radio Frequency cavities, superconductivity in accelerators.
- Applications of accelerators; light sources, medical uses.
- Future: ILC, neutrino factories, muon collider, laser plasma acceleration.

Books
E. Wilson, *An Introduction to Particle Accelerators* OUP
S.Y. Lee *Accelerator Physics* World Scientific (2nd Edition).

Assessment
Written examination of 2½ hours contributing 90%, coursework contributing 10%.

Prerequisites
Second year level electromagnetism.

4472 Order and Excitations in Condensed Matter

Syllabus
The allocation of topics to sessions is shown below. Each session is approximately three lectures.

Atomic Scale Structure of Material (session 1): The rich spectrum of condensed matter; Energy and time scales in condensed matter systems; Crystalline materials: crystal structure as the convolution of lattice and basis; Formal introduction to reciprocal space.
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Magnetism: Moments, Environments and Interactions (session 2) Magnetic moments and angular momentum; diamagnetism and paramagnetism; Hund's rule; Crystal fields; Exchange interactions

Order and Magnetic Structure (session 3) Weiss model of ferromagnetism and antiferromagnetism; Ferrimagnetism; Helical order; Spin Glasses; Magnetism in Metals; Spin-density waves; Kondo effect

Scattering Theory (sessions 4 and 5) X-ray scattering from a free electron (Thomson scattering); Atomic form factors; Scattering from a crystal lattice, Laue Condition and unit cell struture factors; Ewald construction; Dispersion corrections; QM derivation of cross-section; Neutron scattering lengths; Coherent and incoherent scattering

Excitations of Crystalline Materials (session 6) Dispersion curves of 1D monoatomic chain (revision); Understanding of dispersion curves in 3D materials; Examples of force constants in FCC and BCC lattices; Dispersion of 1D diatomic chain; Acoustic and Optic modes in real 3D systems; Phonons and second quantization; Anharmonic interactions

Magnetic Excitations (session 7) Excitations in ferromagnets and antiferromagnets; Magnons; Bloch $T^{3/2}$ law; Excitations in 1, 2 and 3 dimension; Quantum phase transitions

Sources of X-rays and Neutrons (session 8) Full day visit to RAL. Neutron Sources and Instrumentation. Synchrotron Radiation. Applications of Synchrotron Radiation

Modern Spectroscopic Techniques (session 9)
Neutron scattering: triple-axis spectrometer, time-of-flight, polarized neutrons
X-ray scattering: X-ray magnetic circular dichroism, resonant magnetic scattering, reflectivity

Phase transitions and Critical Phenomena (session 10) Broken symmetry and order parameters in condensed matter. Landau theory and its application to structural phase transitions, ferromagnetism, etc. Ising and Heisenberg models. Critical exponents. Universality and scaling

Local Order in Liquids and Amorphous Solids (session 11) Structure of simple liquids; Radial distribution function; Dynamics: viscosity, diffusion; Modelling; Glass formation; Simple and complex glasses; Quasi-crystals

Textbooks
Main texts: Structure and Dynamics: An Atomic View of Materials, Martin T. Dove (OUP); Magnetism in Condensed Matter, Stephen Blundell (OUP)
Additional texts: Elements of Modern X-ray Physics, Jens Als-Nielsen and Des McMorrow (Wiley); Introduction to the Theory of Thermal Neutron Scattering, G.L. Squires (Dover)

Assessment
Examination of 2½ hours duration contributing 90%, coursework 10%.

Prerequisites
UCL's PHYS3C25 – Solid State Physics, or an equivalent from another department

4473 Theoretical Treatments of Nano-systems

Overall aim of the course:
An increasing amount of science and technology is nowadays concerned with processes at the nanometer scale, typically involving functionalized structures like particles and molecules. Time scales of picoseconds are the natural ones to describe the vibrational/conformational properties of these systems, and the relevant steps of their synthesis/assembly mechanisms. Such a high time/size resolution poses extremely demanding constraints to experimental techniques.
A detailed theoretical description and quantum-based numerical modelling have thus become indispensable tools in modern research on this systems, as guides for interpreting the experimental observations and, increasingly, as independent complementary investigation tools, capable of quantitative predictions. The relevant physics at the nanoscale is quantum mechanics, and quantum approaches must be used to provide the potential energy surfaces and the structural/configurational properties which are at the basis of classical molecular dynamics techniques and phase-space descriptions.

This course provides an introduction to the rapidly growing area of atomistic-based theoretical modelling in nano-science, based on fundamental quantum theory. The course introduces the physics of many-electron systems with a particular focus on symmetry properties and on the simplifying assumptions which must be used to successfully model functional nanosized systems. While a main goal of the course is to provide a theoretical background on the structure and quantum behaviour of matter at the nano-scale, examples of applications given during the course involve modern concepts on the nano-scale behaviour of functional materials, and provide an accessible introduction to some of the main theoretical techniques used to model processes involving surfaces, interfaces, clusters, and macromolecules.

Objectives:
On successfully completing this course, a student should:

- Be familiar with the fact that the physical properties of complex nano-systems can be described within a coherent quantum mechanical framework, in particular that the many-electron QM problem can be attacked by mean-field techniques of different levels of complexity

- Understand how this theoretical description can be used as a basis for modelling tools yielding accurate quantum-based potential energy surfaces and inter-atomic force models, and thus is capable of quantitative predictions at the nanometer/picosecond size- and time- scales.

Topics:

(1) **Foundations: mean-field modelling of many electron systems**.
The many-body problem: the general Schroedinger equation problem. The particle exchange operator, symmetry of a two-body wave function with spin. Wavefunction classes constructed from spin orbitals. Reminder of perturbation theory.

Reminder of variational techniques. Example: the virial theorem for Coulombic systems. Variational minimum obtained through self-consistency: derivation of a simple self-consistent Hartree equation for the Helium ground state. Correlation energy. Many electrons: symmetry of the many body wave function under particle exchange. Pauli principle and Slater determinants. The general Hartree-Fock method (outline), electronic correlation in many electron systems. Modern self-consistent approaches: elements of Density Functional Theory.

(2) **Potential energy surfaces and molecular dynamics**.
Quantum molecules: the hamiltonian operator, the Born-Oppenheimer approximation, degrees of freedom of the electronic energy, reminder of the molecular roto-vibration spectrum. The Hellman-Feynman theorem and the concept of classical interatomic force-field. The Verlet Algorithm and First-Principles Molecular Dynamics. Classical potentials, the problem of transferability.

Modelling free energy barriers via thermodynamic integration. Classical dynamics and stochastic processes. Modelling the diffusion of point defects in crystalline solids. The central limit theorem and the evolution of a distribution function. The diffusion coefficient. Derivation of Fick's laws. Examples and exercises.

(3) **Electronic structure, symmetry, case studies**.
Approximate representations for the electronic structure of large molecular systems, derivation of a simple tight-binding scheme (LCAO in the nearest neighbour approximation). The case of aromatic n-rings: model energy multiplets in aromatic systems: HOMO and LUMO levels and the prediction of STM images in negative/positive bias.

The connection between finite and infinite systems: the infinite 1D periodic solid and direct calculation of a model band structure. Bloch states, the Bloch theorem in Born-Von Karman periodic conditions. Other notable symmetries.

If time allows, case study (updated each year), e.g. self-assembly of 2D nanostructures. Construction of a classical force-field and molecular dynamics.

Reading List
1. B. H. Bransden and C. J. Joachain, "Physics of Atoms and Molecules", Prentice Hall (2002) ISBN: 058235692X
2. M. Finnis, "Interatomic Forces in Condensed Matter", Oxford University Press (2003) ISBN: 0198509774
3. M. P. Allen and D. J. Tildesley, "Computer Simulations of Liquids", Clarendon Press (1989) ISBN: 0198556454
4. D. Frenkel and B. Smit, "Understanding Molecular Simulations", Academic Press (2001) ISBN: 0122673514

Assessment:
One three-hour examination contributing 100% of the total marks.

Pre-requisites:
CP3221 Spectroscopy and Quantum Mechanics, or equivalent

4474 Physics at the Nanoscale

Overall aim of the course:
Today an increasing amount of science and technology is concerned with processes at the nano-scale, typified by structures of the order of 10 nanometre in dimension. At this scale, physics is determined by quantum processes, and not by the random (or statistical) processes that dominate in systems of larger sizes. This course provides an introduction to the rapidly growing area of nano-science. Already, nano-structures are 'familiar' to us in the structure of the current generation of computer chips, and the applications of nano-structures are predicted to contribute to the new technologies of this century.
The course introduces the physics and chemistry of nano-structures, discusses their special properties, methods of fabricating them, and some of the methods of analysing them.

Objectives:
On successfully completing this course, a student should:
Appreciate the difference between the physics on the classical (macro-) scale and on the quantum (nano-) scale.
Understand the properties of nanostructures in 'zero', one and two dimensions, their fabrication and their characterisation.

Topics:

Definitions of the nano-scale: the importance of precise structures.
Reminder of some key properties of metals / semiconductors:
Band states, dependence of electron energy on k2, density of electron states.
Fermi surface. Example of use of ideas in de Haas van Alphen effect.
Effective mass. Concept of a hole. Excitons in semiconductors.
Introduction to a classic semiconductor nano-science
Example – GaAs/AlGaAs structures.
Their fabrication by molecular beam epitaxy.
Electrons in a two-dimensional layer:
Quantum mechanics (particle in a box).
Density of electron states.
Verification of energy levels by optical measurements.
Quantum Hall effect.
Superlattices.
Electrons in a one-dimensional system: formation in GaAs/AlGaAs.
Density of states.
Diffusive and ballistic conduction.
Quantised conduction.
Quantum dots:
Fabrication and control of growth in semiconductor/insulator systems by epitaxial processes and by ion-implantation.
Overview of making low-dimensional structures in semiconductor materials: what can be achieved in terms of purity and size control.
The importance of strain as a limit of strained-layer growth, and the use of strain in strain-engineering.

Characteristic sizes:

Characteristic length scales.
Single electron effects on the capacitance and current; Coulomb blockade.
Quantum interference of conduction electrons.
Aharonov-Bohm effect.
Universal conductance fluctuations.

'Top down' fabrication:

Thin layer deposition techniques by thermal evaporation, laser ablation, chemical vapour deposition and MOCVD, plasma-assisted deposition (ECR and Helicon regimes), ion-implanted layers.

'Bottom up' fabrication:

Scanning probe based nano-technology, molecular manufacturing.
Self-organised nano-structures.

Nano-lithography:

Resolution limits.
Electron-beam lithography.
Proximity effect.
Negative and positive lithographic processes.
Electron beam resists.
Ion beam etching and RIBE.
Plasma-assisted etching.
Alignment and self-alignment.
X-ray lithography.
Ion-beam lithography.

Nano-analysis:

SEM- and STEM-based methods.
X-ray and electron spectroscopy.
Scanning tunneling microscopy.
Atomic force microscopy and other scanning probe-based methods, including scanning near field optical microscopy.
Confocal microscopy.

Clean-room environment.

The present. (updated each year).

Assessment:

One three-hour examination contributing 100% of the total marks.

Pre-requisites:

Quantum mechanics at a typical second year level is essential. Condensed matter physics at a typical third year level is desirable but not essential.

4478 Superfluids, Condensates and Superconductors

The extraordinary properties of Superfluids, Superconductors and Bose-Einstein condensates are fascinating manifestations of macroscopic quantum coherence: the fact that the low temperature ordered state is described by a macroscopic wavefunction.

We will study quantum fluids, the superfluidity of liquid ^{4}He and liquid ^{3}He, Bose-Einstein Condensation in dilute gases, metallic superconductivity, as well as the different techniques for achieving low temperatures. It is hoped to emphasize the conceptual links between these very different physical systems. Important developments in this subject were recognised by Nobel prizes in 2003, 2001, 1997, 1996, 1987, 1978, 1973, 1972, 1962 and 1913, which is one measure of its central importance in physics.

Introduction and review of quantum statistics.
The statistical physics of ideal Bose and Fermi gases.
Superfluid ^{4}He and Bose-Einstein condensation.
Phase diagram. Properties of superfluid ^{4}He. Bose-Einstein condensation in ^{4}He. The two-fluid model and superfluid hydrodynamics. Elementary excitations of superfluid ^{4}He. Breakdown of superfluidity. Superfluid order parameter: the macroscopic wavefunction. Quantization of circulation and quantized vortices. Rotating helium.
Bose-Einstein condensation in ultra-cold atomic gases
Cooling and trapping of dilute atomic gases. BEC. Interactions. Macroscopic quantum coherence. Rotating condensates and vortex lattices. The atom laser.
Liquid ^{3}He; the normal Fermi liquid.
Phase diagram. Properties of normal ^{3}He. Quasiparticles. Landau theory of interacting fermions.
Liquid solutions of ^{3}He and ^{4}He.
Isotopic phase separation. Spin polarised ^{3}He.
The properties of quantum fluids in two dimensions
Two dimensional Fermi systems. The superfluidity of 2D ^{4}He; the Kosterlitz-Thouless transition.
Achieving low temperatures
^{3}He-^{4}He dilution refrigerator. Adiabatic demagnetisation of paramagnetic salts. Nuclear adiabatic demagnetisation. Pomeranchuk cooling.
Measurement of low temperatures
Thermal contact and thermometry at trempertures below 1K.
Superfluid ^{3}He.
Superfluid ^{3}He as a model p-wave superfluid. Discovery and identification of the superfluid ground states. ^{3}He-A, the anisotropic superfluid.
Superconductivity
Review of the basic properties of superconductors. Meissner effect. Type I and type II superconductors. Pairing in conventional and unconventional superconductors. Survey of recent advances in novel superconductors.
The Josephson effects.
Josephson effects in superconductors, superfluid ^{4}He and superfluid ^{3}He.

Prerequisites:
This course requires knowledge of base level thermodynamics and statistical physics at year 2/3 level and quantum mechanics at typical year 2 level. A background in solid state physics and superconductivity as covered in a typical year 3 condensed matter course is desirable but not essential.

Books:
Course notes, popular articles, scientific articles and review articles, web based material.
J F Annett, Superconductivity, Superfluids and Condensates, Oxford University Press (2004)
Tony Guénault, Basic Superfluids, Taylor and Francis (2003)
D R Tilley and J Tilley, "Superfluidity and Superconductivity" Adam Hilger.
P M^{c}Clintock, D J Meredith and J K Wigmore, "Matter at Low Temperatures" 1984, Blackie. (Out of print).
J Wilks and D S Betts, "An Introduction to Liquid Helium" 1987, Oxford (out of print).

Assessment:
Written examination of 2½ hours contributing 80%, coursework and essays contributing 20%.

4500 Standard Model Physics and Beyond

Aims and Objectives:
To introduce the student to the Standard Model of Particle Physics, and its minimal supersymmetric extensions. In particular the course will discuss the constituents of the Standard Model and the underlying Lie group structure, within the framework of gauge invariant quantum field theory, which will be introduced to the student in detail, discuss the physical mechanism for mass generation (Higgs), consistently with gauge invariance, and finally present an introduction to (minimal) Supersymmetric Extensions of the Standard Model. In the latter respect, we shall also discuss implications of supersymmetry for astroparticle physics issues, in particular dark matter (provided by the supersymmetric partners) and how astrophysical observations can constrain such particle physics models.

Prerequisites

4242	Relativistic Waves and Quantum Fields	or equivalent
4205	Lie Groups and Lie Algebras.	or equivalent.

4512 Nuclear Magnetic Resonance

This course will be taught at the Royal Holloway campus in Egham

This course will introduce students to the principles and methods of nuclear magnetic resonance. It will apply previously learned concepts to magnetic resonance. Students should appreciate the power and versatility of this technique in a variety of applications.

- Introduction: static and dynamic aspects of magnetism, Larmor precession, relaxation to equilibrium, T_1 and T_2, Bloch equations.

- Pulse and continuous wave methods: time and frequency domains. Manipulation and observation of magnetisation, 90º and 180º pulses, free induction decay.

- Experimental methods of pulse and CW NMR: the spectrometer, magnet. Detection of NMR using SQUIDs.

- Theory of relaxation: transverse relaxation of stationary spins, the effect of motion. Spin lattice relaxation.

- Spin echoes: 'violation' of the Second Law of Thermodynamics, recovery of lost magnetisation. Application to the measurement of T_2 and diffusion.

- Analytical NMR: chemical shifts, metals, NQR.

- NMR imaging: Imaging methods. Fourier reconstruction techniques. Gradient echoes. Imaging other parameters.

Books: B P Cowan, Nuclear Magnetic Resonance and Relaxation, CUP, 1st ed. 1997 and 2nd ed. 2005.
Journal and web references given during course.

Assessment:
Written examination of 2½ hours contributing 90%, coursework contributing 10%.

4515 Computing and Statistical Data Analysis

This course aims to introduce students to programming techniques using the C++ language on a Unix platform. It will also introduce students to techniques of probability and statistical data analysis and they will study applications of data analysis using C++ based computing tools.

- Introduction to C++ and the Unix operating system.
- Variables, types and expressions.
- Functions and the basics of procedural programming.
- I/O and files.
- Basic control structures: branches and loops.
- Arrays, strings, pointers.
- Basic concepts of object oriented programming.
- Probability: definition and interpretation, random variables, probability density functions, expectation values, transformation of variables, error propagation, examples of probability functions.
- The Monte Carlo method: random number generators, transformation method, acceptance-rejection method.
- Statistical tests: significance and power, choice of critical region, goodness-of-fit.
- Parameter estimation: samples, estimators, bias, method of maximum likelihood, method of least squares, interval estimation, setting limits, unfolding.

Books: R. Miller, An Introduction to the Imperative Part of C++, www.doc.ic.ac.uk/~wjk/C++Intro.
W. Savitch, Problem Solving with C++: The Object of Programming, 4th Ed., Addison-Wesley, 2003.
G D Cowan, Statistical Data Analysis, Clarendon Press, 1998.
R J Barlow, Statistics: A Guide to the Use of Statistical Methods in the Physical Sciences, John Wiley, 1989.

Assessment:
Written examination of 2½ hours contributing 70%, coursework contributing 30%.

4534 String Theory and Branes

Aims and Objectives:
The main aim of the course is to give a first introduction to string theory which can be used as a basis for undertaking research in this and related subjects.

Syllabus:
Topics will include the following: classical and quantum dynamics of the point particle, classical and quantum dynamics of strings in spacetime, D-branes, the spacetime effective action, and compactification of higher dimensions.

Web page: http://www.mth.kcl.ac.uk/courses

Teaching Arrangements:
Two hours of lectures each week

Prerequisites:
The course assumes that the students have an understanding of special relativity and quantum field theory. In addition the student should be familiar with General Relativity, or be taking the Advanced General Relativity course concurrently.

Assessment:
The course will be assessed by a two-hour written examination at the end of the academic year.

Assignments:
During the lectures problems will be given and complete solutions will be made available. It is crucial that students work through these problems on their own.

Reading List:
The lecture notes taken during the lectures are the main source. However, some of the material is covered in:

- Green, Schwarz and Witten: String Theory 1, Cambridge University Press.
- B. Zwiebach: A First Course in String Theory, Cambridge University Press.

4541 Supersymmetry and Gauge Symmetry

Aims and objectives:
This course aims to provide an introduction to two of the most important concepts in modern theoretical particle physics; gauge theory, which forms the basis of the Standard Model, and supersymmetry. While gauge theory is known to play a central role in Nature, supersymmetry has not yet been observed but nevertheless forms a central pillar in modern theoretical physics.

Syllabus:
Maxwell's equations as a gauge theory. Yang-Mills theories. Supersymmetry. Vacuum moduli spaces, extended supersymmertry and BPS monopoles.

Web page: http://www.mth.kcl.ac.uk/courses

Teaching arrangements:
Two hours of lectures each week

Prerequisites:
Students should be familiar with quantum field theory, special relativity as well as an elementary knowledge of Lie algebras.

Assessment:
The courses will be assessed by a two hour written examination at the end of the academic year.

Assignments:
During the lectures problems will be given and complete solutions will be made available. It is crucial that students work through these problems on their own.

Books:
The lecture notes taken during the lectures are the main source but see also

- D. Bailin and A. Love: Supersymmetric Gauge Field Theory and String Theory, Taylor and Francis.
- L. Ryder: Quantum Field Theory, Cambridge University Press
- P. West: Introduction to Supersymmetry, World Scientific

4600 Stellar Structure and Evolution

Course outline
Stars are important constituents of the universe. This course starts from well known physical phenomena such as gravity, mass conservation, pressure balance, radiative transfer of energy and energy generation from the conversion of hydrogen to helium. From these, it deduces stellar properties that can be observed (that is, luminosity and effective temperature or their equivalents such as magnitude and colour) and compares the theoretical with the actual. In general good agreement is obtained but with a few discrepancies so that for a few classes of stars, other physical effects such as convection, gravitational energy generation and degeneracy pressure have to be included. This allows an understanding of pre-main sequence and dwarf stages of evolution of stars, as well as the helium flash and supernova stages.

Syllabus – Topics covered include:

- Observational properties of stars, the H-R diagram, the main sequence, giants and white dwarfs.

- Properties of stellar interiors: radiative transfer, equation of state, nuclear reactions, convection.

- Models of main sequence stars with low, moderate and high mass.

- Pre- and post-main sequence evolution, models of red giants, and the end state of stars.

The course includes some exposure to simple numerical techniques of stellar structure and evolution; computer codes in Fortran.

Prerequisites: some knowledge of Fluids, Electromagnetism, Stellar Structure

Books: Course Notes available **+** R Kippenhahn and A Weigert - Stellar Structure and Evolution Springer

Assessment: Written examination of 3 hours contributing 100%

4601 Advanced Cosmology

Course outline
Cosmology is a rapidly developing subject that is the focus of a considerable research effort worldwide. It is the attempt to understand the present state of the universe as a whole and thereby shed light on its origin and ultimate fate. Why is the universe structured today in the way that it is, how did it develop into its current form and what will happen to it in the future? The aim of this course is to address these and related questions from both the observational and theoretical perspectives. The course does not require specialist astronomical knowledge and does not assume any prior understanding of general relativity.

Syllabus

- Observational basis for cosmological theories.
- Derivation of the Friedmann models and their properties.
- Cosmological tests; the Hubble constant; the age of the universe; the density parameter; luminosity distance and redshift.
- The cosmological constant.
- Physics of the early universe; primordial nucleosynthesis; the cosmic microwave background (CMB); the decoupling era; problems of the Big Bang model.
- Inflationary cosmology.
- Galaxy formation and the growth of fluctuations
- Evidence for dark matter.
- Large and small scale anisotropy in the CMB.

Prerequisites: Knowledge of Newtonian Dynamics and Gravitation, and Calculus.

Books:

Assessment: Written examination of 3 hours contributing 100%

4602 Relativity and Gravitation

- Introduction to General Relativity.
- Derivation from the basic principles of Schwarzschild.
- Solution of Einstein's field equations.
- Reisner-Nordstrom, Kerr and Kerr-Neuman solutions and physical aspects of strong gravitational fields around black holes.
- Generation, propagation and detection of gravitational waves.
- Weak general relativistic effects in the Solar System and binary pulsars.
- Alternative theories of gravity and experimental tests of General Relativity.

Prerequisites: knowledge of Relativity

Books:

Assessment: Written examination of 3 hours contributing 100%.

4603 Astrophysical Fluid Dynamics

Course outline
This course studies the structure and dynamical behaviour a variety of astrophysical regimes, using the basic equations of fluid dynamics. Starting from the simplest applications, such as sound-waves and gravitational instability, it proceeds to topics of current research, such as solar and stellar seismology. It considers the influence of rotation at the initial stages of gravitational collapse, which leads eventually to the formation of compact objects, rotational distortion of stellar and planetary configurations, and tidal interaction in binary stars. The course also considers settings where nonlinear equations are applicable, such as spherically-symmetric accretion of gaseous clouds, and addresses briefly the formation and evolution of nonlinear waves and shocks.

Syllabus

- Fluid dynamical model in astrophysics.
- Gravitational stability, gravitational collapse.
- Stellar stability, stellar oscillations, variable stars.
- Helioseismology.
- Stellar rotation, structure of rotating stars.
- Binary stars, tidally distorted models.
- Rotationally and tidally distorted planets.

Prerequisite: An introductory course on fluid dynamics, and astrophysics.

Book: F. H. Shu, The physics of astrophysics, Vol II: Gas dynamics, 1992 University Science Books: Mill Valley, CA.

Assessment: Written examination of 3 hours contributing 100%.

4630 Planetary Atmospheres

Comparison of the Planetary Atmospheres (2 lectures)
The radiative energy balance of a planetary atmosphere; the competition between gravitational attraction and thermal escape processes. The factors which influence planetary atmospheres; energy and momentum sources; accretion and generation of gases; loss processes; dynamics; composition.
Atmospheric structure (7 lectures)
Hydrostatic equilibrium, adiabatic lapse rate, convective stability, radiative transfer, the greenhouse effect and the terrestrial planets.
Oxygen chemistry (3 lectures)
Ozone production by Chapman theory; comparison with observations; ozone depletion and the Antarctic ozone hole.
Atmospheric temperature profiles (3 lectures)
Troposphere, stratosphere, mesosphere, thermosphere and ionosphere described; use of temperature profiles to deduce energy balance; internal energy sources; techniques of measurement for remote planets.
Origin of planetary atmospheres and their subsequent evolution (3 lectures)
Formation of the planets; primeval atmospheres; generation of volatile material; evolutionary processes; use of isotopic abundances in deducing evolutionary effects; role of the biomass at Earth; consideration of the terrestrial planets and the outer planets.
Atmospheric Dynamics (4 lectures)
Equations of motion; geostrophic and cyclostrophic circulation, storms; gradient and thermal winds; dynamics of the atmospheres of the planets; Martian dust storms, the Great Red Spot at Jupiter.
Magnetospheric Effects (1 lecture)
Ionisation and recombination processes; interaction of the solar wind with planets and atmospheres; auroral energy input.
Atmospheric loss mechanisms (1 lecture)
Exosphere and Jeans escape; non thermal escape processes; solar wind scavenging at Mars.
Observational techniques (3 lectures)
Occultation methods from ultraviolet to radiofrequencies; limb observation techniques; in-situ probes.
Global warming (3 lectures)
Recent trends and the influence of human activity; carbon budget for the Earth; positive and negative feedback effects; climate history; the Gaia hypothesis; terraforming Mars.

Books:
J. W. Chamberlain and D. M. Hunten, "Theory of Planetary Atmospheres" Academic Press.
M. Salby, "Introduction to Atmospheric Physics", Academic Press.
J. T. Houghton, "The Physics of Atmospheres", Cambridge University Press.

Assessment:
Examination of 2½ hours duration contributing 90%, coursework 10%.

4640 Solar Physics

1. **Introduction**
Presentation of the syllabus and suggested reading, a list of solar parameters and a summary of the topics to be treated during the course. (1)

2. **The Solar Interior and Photosphere**
Stellar Structure and Evolution. Life history of a star. Equations and results. Conditions for Convection. Arrival of the Sun on the Main Sequence. Nuclear fusion reactions. The Standard Solar Model. Neutrino production and Detection – the neutrino problem. Solar Rotation. Photospheric models and observations. Fraunhofer lines. Chemical composition. Convection and Granulation. Waves and oscillations – Helioseismology or probing the SunUs interior. (12)

3. **Solar Magnetic Fields/Solar Activity**
Sunspot observations – structure, birth and evolution. Spot temperatures and dynamics. Observations of faculae. Solar magnetism – Sunspot and Photospheric fields. Active Region manifestations and evolution. Solar Magnetic Cycle – Observations and Dynamics. Babcock dynamo model of the solar cycle. Behaviour of flux tubes. Time behaviour of the Sun's magnetic field. (4)

4. **The Solar Atmosphere - Chromosphere**
Appearance of the Chromosphere – Spicules, mottles and the network. Observed spectrum lines. Element abundances. Temperature profile and energy flux. Models of the Chromosphere. Nature of the Chromosphere and possible heating mechanisms. (4)

5. **The Solar Atmosphere - Corona and Solar Wind**
Nature and appearance of the corona. Breakdown of LTE. Ionization/ recombination balance and atomic processes. Spectroscopic observations and emission line intensities. Plasma diagnostics using X-ray emission lines. Radio emission. Summary of coronal properties. Discovery of the solar wind. X-ray emission and coronal holes. In-situ measurements and the interplanetary magnetic field structure. Solar wind dynamics. Outline of the Heliosphere. (6)

6. **Solar Flares.**
Flare observations throughout the solar atmosphere. Thermal and non-thermal phenomena. Particle acceleration and energy transport. Gamma-ray production. Flare models and the role of magnetic fields. (3)

Assessment:
Examination of 2½ hours duration contributing 90%, coursework 10%.

4650 Solar System

Course outline

As the planetary system most familiar to us, the Solar System presents the best opportunity to study questions about the origin of life and how enormous complexity arise from simple physical systems in general. This course surveys the physical and dynamical properties of the Solar System. It focuses on the formation, evolution, structure, and interaction of the Sun, planets, satellites, rings, asteroids, and comets. The course applies basic physical and mathematical principles needed for the study, such as fluid dynamics, electrodynamics, orbital dynamics, solid mechanics, and elementary differential equations. However, prior knowledge in these topics is not needed, as they will be introduced as required. The course will also include discussions of very recent, exciting developments in the formation of planetary and satellite systems and extrasolar planets (planetary migration, giant impacts, and exoplanetary atmospheres).

Syllabus

- General overview/survey.
- Fundamentals: 2-body problem, continuum equations.
- Terrestrial planets: interiors, atmospheres.
- Giant planets: interiors, atmospheres.
- Satellites: 3-body problem, tides.
- Resonances and rings.
- Solar nebula and planet formation.
- Asteroids, comets and impacts.

Assessment: Written examination of 3 hours contributing 100%

Book: C.D. Murray and S.F. Dermott, Solar System Dynamics, Cambridge University
Press.

4660 The Galaxy

Course outline
The course considers in detail the basic physical processes that operate in galaxies, using our own Galaxy as a detailed example. This includes the dynamics and interactions of stars, and how their motions can be described mathematically. The interstellar medium is described and models are used to represent how the abundances of chemical elements have changed during the lifetime of the Galaxy. Dark matter can be studied using rotation curves of galaxies, and through the way that gravitational lensing by dark matter affects light. The various topics are then put together to provide an understanding of how the galaxies formed.

Syllabus

- Introduction: galaxy types, descriptive formation and dynamics.
- Stellar dynamics: virial theorem, dynamical and relaxation times, collisionless Boltzmann equation, orbits, simple distribution functions, Jeans equations.
- The interstellar medium: emission processes from gas and dust (qualitative only), models for chemical enrichment.
- Dark matter - rotation curves: bulge, disk, and halo contributions.
- Dark matter - gravitational lensing: basic lensing theory, microlensing optical depth.
- The Milky Way: mass via the timing argument, solar neighbourhood kinematics, the bulge, the Sgr dwarf.

Assessment: Written examination of 3 hours contributing 100%

References: Shu for some basic material, Binney & Merrifield and Binney & Tremaine for some topics, plus full course notes.

4670 Astrophysical Plasmas

- The plasma state as found in astrophysical contexts.
- Particle motion in electromagnetic fields, cyclotron motion, drifts and mirroring, with application to the radiation belts and emission from radio galaxies.
- Concepts of magnetohydrodynamics (MHD); flux freezing and instabilities.
- The solar wind, including MHD aspects, effects of solar activity, and impact on the terrestrial environment.
- Magnetic reconnection; models and application to planetary magnetic storms and stellar flares and coronal heating.
- Shock waves and charged particle acceleration.

Assessment: Examination of 2½ hours duration contributing 90%, coursework 10%.

4680 Space Plasma and Magnetospheric Physics

Introduction [1]
Plasmas in the solar system, solar effects on Earth, historical context of the development of this rapidly developing field
Plasmas [3]
What is a plasma, and what is special about space plasmas; Debye shielding, introduction to different theoretical methods of describing plasmas
Single Particle Theory [6]
Particle motion in various electric and magnetic field configurations; magnetic mirrors; adiabatic invariants; particle energisation
Earth's Radiation Belts [3]
Observed particle populations; bounce motion, drift motion; South Atlantic Anomaly; drift shell splitting; source and acceleration of radiation belt particles; transport and loss of radiation belt particles
Introduction to Magnetohydrodynamics [3]
Limits of applicability; convective derivative; pressure tensor; continuity equation; charge conservation and field aligned currents; equation of motion; generalised Ohm's law; frozen-in flow; magnetic diffusion; equation of state; fluid drifts; magnetic pressure and tension
The Solar Wind [3]
Introduction, including concept of heliosphere; fluid model of the solar wind (Parker); interplanetary magnetic field and sector structure; fast and slow solar wind; solar wind at Earth; coronal mass ejections
The Solar Wind Interaction with Unmagnetised Bodies [2]
The Moon; Venus, Comets
The Solar Wind and Magnetised Bodies (I) [4]
Closed Magnetosphere Model
The ring current, boundary currents; shape of the magnetopause; corotation; convection driven by viscous flow
The Solar Wind and Magnetised Bodies (II) [3]
Open Magnetosphere Model, Steady State
Magnetic reconnection; steady state convection; currents and potentials in an open magnetosphere; the magnetotail; the plasmasphere; the aurorae
The Solar Wind and Magnetised Bodies (III) [2]
Open Magnetosphere Model, Non-Steady State
Phases of a substorm; Substorm current systems and unanswered questions about substorms; magnetic storms; dayside reconnection.

Books: M.Kivelson and C.T.Russell, Introduction to space physics, Cambridge University Press, W.Baumjohann and R.Treumann, Basic space plasma physics, Imperial College Press

Assessment: Written Examination, 2½ hours, contributing 90%, coursework 10%.

Prerequisites: While the course is essentially self-contained, some knowledge of basic electromagnetism and mathematical methods is required. In particular it is assumed that the students are familiar with Maxwell's equations and related vector algebra.

4690 Extrasolar Planets and Astrophysical Discs

Course outline

Ever since the dawn of civilisation, human beings have speculated about the existence of planets outside of the Solar System orbiting other stars. The first bona fide extrasolar planet orbiting an ordinary main sequence star was discovered in 1995, and subsequent planet searches have uncovered the existence of more than one hundred planetary systems in the Solar neighbourhood of our galaxy. These discoveries have reignited speculation and scientific study concerning the possibility of life existing outside of the Solar System.

This module provides an in-depth description of our current knowledge and understanding of these extrasolar planets. Their statistical and physical properties are described and contrasted with the planets in our Solar System. Our understanding of how planetary systems form in the discs of gas and dust observed to exist around young stars will be explored, and current scientific ideas about the origin of life will be discussed. Rotationally supported discs of gas (and dust) are not only important for explaining the formation of planetary systems, but also play an important role in a large number of astrophysical phenomena such as Cataclysmic Variables, X-ray binary systems, and active galactic nuclei. These so-called accretion discs provide the engine for some of the most energetic phenomena in the universe.

The second half of this module will describe the observational evidence for accretion discs and current theories for accretion disc evolution.

4800 Molecular Biophysics

Aims of the Course
The course will provide the students with insights in the physical concepts of some of the most fascinating processes that have been discovered in the last decades: those underpinning the molecular machinery of the biological cell. These concepts will be introduced and illustrated by a wide range of phenomena and processes in the cell, including biomolecular structure, DNA packing in the genome, molecular motors and neural signalling.
The aim of the course is therefore to provide students with:

- Knowledge and understanding of physical concepts that are relevant for understanding biology at the micro- to nano-scale.
- Knowledge and understanding of how these concepts are applied to describe various processes in the biological cell.

Objectives

- After completing this half-unit course, students should be able to:
- Give a general description of the biological cell and its contents
- Explain the concepts of free energy and Boltzmann distribution and discuss osmotic pressure, protein structure, ligand-receptor binding and ATP hydrolysis in terms of these concepts.
- Explain the statistical-mechanical two-state model, describe ligand-receptor binding and phosphorylation as two-state systems and give examples of “cooperative” binding.
- Describe how polymer structure can be viewed as the result of random walk, using the concept of persistence length, and discuss DNA and single-molecular mechanics in terms of this model
- Explain the worm-like chain model and describe the energetics of DNA bending and packing; explain how such models are relevant for the rigidity of cells
- Explain the low Reynolds-number limit of the Navier-Stoke's equation and discuss its consequences for dynamics in biological systems
- Explain simple solutions of the diffusion equation in biological systems and their consequences for diffusion and transport in cells
- Explain the concept of rate equations and apply it to step-wise molecular reactions
- Give an overview of the physical concepts involved in molecular motors and apply them to obtain a quantitative description of motor driven motion and force generation
- Describe neural signalling in terms of propagating (Nernst) action potentials and ion channel kinetics
- Link the material in the course to at least one specific example of research in the recent scientific literature

Syllabus
(The approximate allocation of lectures to topics is given in brackets below.)
Biological cells [3]

Introduction to the biology of the cell – cell types – cell components – DNA, RNA, proteins, lipids, polysaccharides – overview of functional processes in cells
Statistical mechanics in the cell [4]
Deterministic versus thermal forces – free-energy minimisation and entropy, Boltzmann distribution – free energy of dilute solutions, osmotic pressure/forces – consequences for protein structure and hydrophobicity – equilibrium constants for ligand-receptor binding and ATP hydrolysis
Two-state systems [3]
Biomolecules with multiple states – Gibbs distribution – ligand-receptor binding, phosphorylation – "cooperative" binding
Structure of macromolecules [3]
Random walk models of polymers – entropy, elastic properties and persistence length of polymers – DNA looping, condensation and melting – single-molecule mechanics
Elastic-rod theory for (biological) macromolecules [3]
Beam deformation and persistence length – worm-like chain model – beam theory applied to DNA – cytoskeleton
Motion in biological environment [4]
Navier-Stokes equation – viscosity and Reynold's number in cells – diffusion equation and its solutions – transport and signalling in cells – diffusion limited reactions
Rate equations and dynamics in the cell [3]
Chemical concentrations determine reaction rates – rate equations for step-wise molecular reactions – Michaelis-Menten kinetics
Molecular motors [4]
Molecular motors in the cell – rectified Brownian motion – diffusion equation for a molecular motor – energy states and two-state model for molecular motors – force generation by polymerisation
Action potentials in nerve cells [3]
Nerst potentials for ions – two-state model for ion channels – propagation of action potentials – channel conductance

Prerequisites
It is recommended but not mandatory that students have taken second level Thermal Physics. Second level Statistical Thermodynamics would be useful but is not essential. The required concepts in statistical mechanics will be (re-)introduced during the course.

Methodology and Assessment
This is a half-unit course, with 30 lectures and 3 discussion/problems classes. Basic problem-solving skills will be stimulated by the setting of a weekly problem question. The answers will be collected weekly and more extensively discussed during the discussion/problem classes. The marks on these problem questions account for 10% of the overall course assessment. The remaining 90% is determined via an unseen written examination.

Textbooks
The course will make extensive use of the following book, parts of which will be obligatory reading material:

- Physical Biology of the Cell, 1st Edition, R. Phillips, J. Kondev, and J. Theriot, Garland Science 2009.

Other books which may be useful include the following. They cover more material than is in the syllabus.

- Biological Physics, 1st Edition, Philip Nelson, W.H. Freeman., 2004.
- Mechanics of Motor Proteins and the Cytoskeleton, 1st Edition, J. Howard, Sinauer Associates, 2001.
- Protein Physics, 1st Edition, A.V. Finkelstein and O.B. Ptitsyn, Academic Press, 2002.
- Molecular Driving Forces, 1st Edition, K.A. Dill and S. Bromberg, Garland Science, 2003.

The following books may be useful for biological reference.

- Molecular Biology of the Cell, 4th Edition, B. Alberts et al., Garland Science, 2002.
- Cell Biology, 2nd Edition, T.D. Pollard, W.C. Earnshaw and J. Lippincott-Schwartz, Elsevier, 2007.