Imperial College London

The Blackett Laboratory

Theoretical Physics Group

Quantum Fields and Fundamental Forces

MSc Course Handbook 2020-2021

This document is primarily for MSc students on the Quantum Fields and Fundamental Forces course, and contains detailed information about the MSc course, computer resources, and more general information about working in the Theory Group and at Imperial. It also serves as a useful introduction to the Theory Group for PhD students, postdocs and visitors.

October 2020

Contents

I. Information for MSc Students

Welcome to the MSc course on Quantum Fields and Fundamental Forces! These notes are intended to supply students with some essential information about the course.

1 Introduction and General Information

The Theoretical Physics Group is internationally recognised for its contribution to our understanding of the unification of fundamental forces, the early universe, quantum gravity, supersymmetry, string theory, and many other aspects of quantum field theory. This MSc course is intended to bridge the gap between an undergraduate course in Physics or Mathematics and the research frontier in fundamental theoretical physics.

1.1. Aims and Objectives

The formal aim of the MSc Course, Quantum Fields and Fundamental Forces is:

- to provide a high quality education in theoretical physics which brings students up to the frontiers of knowledge and prepares them for research.

At the end of the course, MSc graduates will have achieved the following objectives:

- acquired an understanding of quantum field theory, its mathematical techniques, and its applications to fundamental forces and to physics generally.
- learned research skills by undertaking a supervised independent Dissertation.

1.2. Staff Members

The MSc course lectures are given by staff of the Theoretical Physics Group, one of nine Groups in the Physics Department at Imperial College. The current staff (and some of their duties) are

- Prof. K.S. Stelle (QFFF Course Director)
- Prof. J. Halliwell (QFFF Course Admissions)
- Prof. D. Waldram (Head of Theoretical Physics Group)
- Prof. A. Tolley (PhD Admissions)
- Prof. A. Rajantie
- Prof. C. Contaldi
- Prof. C. de Rham
- Prof. H.F. Dowker
- Dr. T.S. Evans

- Prof. J. Gauntlett
- Prof. A. Hanany
- Prof. C.M. Hull FRS
- Prof. J. Magueijo
- Prof. A. Tseytlin
- Prof. T. Wiseman
- Prof. M.J. Duff FRS (Senior Research Fellow)
- Prof. C.J. Isham (Senior Research Fellow)
- Dr. H.F. Jones (Senior Research Fellow)
- Prof. R.J. Rivers (Senior Research Fellow)

In addition, the Theoretical Physics Group has a number of Postdoctoral Research Assistants and Visiting Research Fellows, and about twenty PhD students. The total community typically comprises seventy or more physicists.

1.3. Personal Tutors and Other Points of Contact

Every MSc student is assigned a member of the academic staff as Personal Tutor at the beginning of the course. The role of the Personal Tutor is primarily to be the first point of contact for any issues or difficulties that may arise throughout the course. He or she will be able to advise students on selection of courses, career matters, writing recommendation letters, and also any matters of a non-academic nature. Another contact for more personal matters is Arnaud Czaja, the Physics Department Postgraduate Advisor, who may be reached on Ext.41789. See also the website `http://www3.imperial.ac.uk/counselling` for more information.

Shortly after the start of the year, the MSc student body is asked to appoint a representative, whose role is to act as a channel between students and staff for any general matters that may arise. The student representative, who should be a full-time QFFF student, will also be invited to attend the Physics Department's PGT (Postgraduate Taught Course) committee meetings. Another contact person is the Departmental PG representative, who oversees the organisation of Departmental social events for postgraduate students.

1.4

Special conditions for the 2020-2021 academic year. Owing to the medical situation resulting from the coronavirus, all courses in the autumn term will be given online, using Microsoft Teams. We very much hope to return to delivering lectures and other engagements such as Rapid Feedback sessions when this becomes possible, but it is not possible to predict when that might be the case. In general, courses organised by the undergraduate system will be taught online in an asynchronous fashion, probably for the entire 2020-21 academic year. Asynchronous courses will be pre-recorded and can be viewed at any time. Those courses include Quantum Field Theory, Unification and the allowed undergraduate coursed listed in Section 2. Courses organised by the QFFF faculty will be

taught in synchronous fashion, on the other hand, *i.e.* at stated times given in the course timetable. These courses include Particle Symmetries, QED and the Optional MSc courses listed in Section 2.

In order to encourage development of a group spirit for the QFFF class, we aim to group students into sets of smaller cohorts which we hope will lead to discussions and joint learning even under the conditions of mostly online interaction.

General comments about Life in the Theoretical Physics Group given in Section IV are in many cases not directly relevant to the 2020-21 academic year, but have been left in the Handbook for general background information.

2 Structure of the Course.

2.1 Courses Available

The following list of courses was correct at the time of writing, but courses frequently change due to changes in staff.

Compulsory Courses:

- Particle Symmetries – Prof. Waldram
- Quantum Field Theory – Prof. Wiseman
- Quantum Electrodynamics – Prof. Wiseman
- Unification – Prof. Rajantie

Optional Courses:

- Advanced Field Theory – Prof. Tolley
- Supersymmetry – Prof. Hanany
- Relativity and Cosmology – Prof. Magueijo
- Black Holes – Prof. Stelle
- Differential Geometry – Prof. Hull
- String Theory – Prof. Tseytlin
- The Standard Model and Beyond – Prof. Stelle

Undergraduate Courses:

- Foundations of Quantum Theory – Prof. Tolley
- Group Theory – Dr. Averbukh (Quantum Optics and Laser Science Group)
- General Relativity – Prof. Gauntlett

- Quantum Theory of Matter – Prof. Dimitri Vvedensky (Condensed Matter Theory Group)
- Quantum Information – Prof. Myungshik Kim (Quantum Optics and Laser Science Group)

2.2 Course Requirements

Students must take four Compulsory courses: Quantum Field Theory, Quantum Electrodynamics, Unification, and Particle Symmetries. In addition, students must take four or more optional courses which can include up to two of the approved optional undergraduate courses from the above list. MSc students are advised to discuss their choice of courses with their Personal Tutor if they are uncertain about their course programme. Students thinking about doing a PhD after their MSc are advised to choose courses closely related to their intended area of PhD research.

Imperial College graduates may already have taken some of the offered courses. In this case, they may not offer a course for examination a second time. Imperial College graduates who have already taken the Compulsory Quantum Field Theory or Unification courses should take Advanced Field Theory instead. An Imperial College graduate who has already taken both Quantum Field Theory and Unification should replace the second ineligible course with an MSc-level course (*i.e.* not an undergraduate course).

Part-time students must be examined on one Compulsory course and two Optional courses during their first year.

2.3 Timetable

The course lasts one calendar year full time (or two years part time). It begins in October, with formal coursework ending by June and project work occupying the summer vacation. The College standard lecturing schedule is followed, with 50 minute lectures commencing on the hour, Monday to Friday 9am to 6pm, with Wednesday afternoons free. The total number of lectures per week on the MSc course depends on the choice of courses, but it typically totals about 15 lectures.

The Compulsory QFT, Unification and Particle Symmetries lectures take place in the first term, along with the optional Differential Geometry course. These lecture courses start at a reasonably low level in order to make sure that everyone is up to speed in classical and quantum mechanics, group theory and relativity. We strongly suggest that students attend at least the first few weeks of the undergraduate General Relativity course to review tensor notation, even if they don't attend the entire course. As with the other undergraduate courses, this course may also be viewed using the panopto system, which may reduce pressure on the lecture theatres. The Quantum Electrodynamics course begins late in the autumn term and continues into the beginning of the winter term.

Lectures for the remaining optional courses take place in the second term. The approved undergraduate courses are spread throughout the first and second term.

After the New Year, there will be two tests (each two hours long) on the first term's courses, one on Particle Symmetries and Unification, the other on QFT. These tests do not count towards the final mark so students are not obliged to take them, but they are strongly recommended, since the results are important in assisting staff members to write recommendation letters for PhD applications (which are generally scheduled in the second term).

The first and second term courses are examined in the third term, over a period of approximately six weeks from late April into early June.

After the exams have finished in June, there will be a series of Special Topics lectures, in which postdocs and staff members talk about their research interests. These are a good source of

inspiration for the MSc Dissertation, work on which will fill up the rest of the summer.

By about the beginning of July students should have a clear idea of their Dissertation topic and communicate a preliminary title to the Course Director. A preliminary draft of the Dissertation should be available for perusal by the Dissertation Advisor (who in many cases will be different from the Personal Tutor) in early September, and the final deadline is usually the third Friday in September (you will be informed in due course of the precise date). More details about the MSc Dissertation may be found in Section II.

Final assessment, at the examiners meeting in November, is made on the basis of eight examinations and the Dissertation.

The quality of the lecture courses is monitored through questionnaires at the end of each course, and also by lecturers occasionally sitting in on each other's lectures. Students are invited to fill out questionnaires specific to the QFFF course, as well as the SOLE evaluation which is run by the College Registry.

The QFFF MSc class should choose a Student Representative during the autumn term, to serve as contact person between the class and the College. Constructive comments about the course from students are welcome at any time, either made directly to a lecturer, or passed through a Personal Tutor or through the Student Representative.

Students are also welcome to attend the wide range of research seminars given at Imperial (and also other London colleges). Staff may recommend seminars that are particularly accessible. Also of interest are the Physics Department colloquia, about three times per term, designed to appeal to a wide audience.

3 Course Requirements

The basic requirements for an overall Pass in the MSc are as follows.

- According to Imperial College London regulations, the QFFF course is divided into three "Elements": 1) the four Compulsory Courses, 2) four Optional Courses and 3) the Dissertation. A complete set of eight course exams must be presented and passed in order to pass the MSc, with the Pass mark set at 50%. Failing this, exams will have to be resat. Cases involving a single failure may, upon occasion, be dealt with by a viva, upon recommendation of the QFFF Board of Examiners. College regulations limit the mark received in any such resit or viva to a bare (50%) Pass.

- All three Elements (Compulsory, Optional and Dissertation) must be passed at the 50% level.

- Satisfactory results for the two examination Elements (Compulsory exams and Optional exams) of the QFFF course allow for some averaging within an Element. Individual course exams with marginal failures in the 40% to 50% range may be averaged together with other exams in the same Element, providing the overall average for the Element is at least 50%.

- The Dissertation must be passed with a mark of at least 50%.

Formal decisions on Passes and Failures are made at the QFFF course final Examiners' Meeting, which is generally held in November following the assessment of the MSc Dissertations. Good performance in the New Year tests may sometimes be used to compensate for a marginal (40%-50%) course exam failure. Preliminary decisions on performance in the written exams are made

in an examiners meeting held in early summer. Students are informed at that time whether resit examinations are needed. Resits for failed examinations are normally taken at the next available opportunity which will generally be in the following academic year. For some courses organised by the undergraduate course system (*i.e.* Quantum Field Theory, Unification and the listed undergraduate courses), there may be resits organised during the current academic year in the month of September. QFFF students may arrange to take such earlier resits, but they will have to register for this with the undergraduate examiners.

A given course may be resat only once.

Owing to the limitation to a bare 50% Pass result for resit examinations (except for those occasioned by special circumstances such as an illness attested to by a doctor's certificate and for which a mitigating circumstances form has been submitted), students are *strongly recommended to take exams in nine or more courses.* Results in the best set making up complete Compulsory and Optional Elements will be counted. If there is some chance that you may miss an exam for unavoidable reasons, make sure that you consult with the MSc Course Director beforehand.

The award of a Distinction or a Merit on the QFFF course is at the discretion of the Board of Examiners. The rough guidelines are as for Passes, substituting the Distinction level of 70% or the Merit level of 60% for the 50% Pass level. According to the QFFF guidelines, averaging within Elements may be allowed for marks falling short of the Distinction target as follows: marks in the 60%-70% range may be averaged against higher marks within an Element, provided the average mark of the Element is at least 70. The award of Distinction and Merit MSc degrees is decided by the QFFF faculty in the final (November) Examiners Meeting; they are not automatically given. In general, averaging of course examination marks will not be allowed for the award of a Merit degree: every course examination mark must reach the required level of 60%. Exceptions to this rule may be considered by the Board of Examiners in cases where just one exam falls slightly short of the 60% mark; candidates whose averages fall within 2.5% of a boundary will be considered for promotion in this way.

In addition, the MSc Dissertation must in all cases obtain a mark at or above the minimum corresponding level (70% for a Distinction, 60% for a Merit).

The above regulations are stated in the formal marking scheme of Imperial College London, where the Pass level is set at 50% and the Distinction level is set at 70%. Students should be aware that the marking of individual courses may be subject to scaling procedures, so the above percentage marks, which correspond to those that will appear on final course transcripts, may differ from those used internally by the examiners in marking specific exam questions. In particular, the QFFF standard for a Distinction is set particularly high. On a straight linear marking scale, the standard required for a Distinction is closer to 80% than to the 70% level which will be represented on transcripts.

4 QFFF Course syllabuses: Compulsory Courses

TP.1 Particle Symmetries

Prof. Waldram
30 hours
Introduction Role of symmetry in physics. Basic introduction to symmetries and particles of the standard model.
Group Theory Introduction to group theory and representation theory. Brief discussion of finite groups. Matrix groups and the notion of Lie groups.
Lie Groups The main part of the course is the treatment of Lie groups, Lie algebras and their representation theory. $SU(2)$ and $SU(3)$ and their representations are discussed in detail. Poincaré group and Lorentz group and their representations. Heisenberg group and its representations.
Applications Throughout the course we will discuss specific applications of Lie groups to particle physics.

TP.2 Quantum Field Theory

Prof. Wiseman
27 hours
Introduction. Basic aims and ideas of field theory. Types of field and relationship to symmetries (relativistic, non-relativistic and other particle symmetries).
Review of Classical Field Theory Lagrangian and Hamiltonian descriptions of field theory. Linearity and interactions. Internal symmetries and Noether's theorem.
Quantisation of a Scalar Field Plane wave solutions of the Klein Gordon equation. Quantisation and commutation relations. Creation and annihilation operators. Complex scalar fields and their conserved charge.
Interacting QFT. Crosssections, matrix elements and vacuum expectation values. Wick's theorem and normal ordering. Simple Feynman diagrams (without renormalisation). For a real scalar field. Possible extension to complex scalar field.
Further Topics. To be added as time allows

TP.3 Quantum Electrodynamics

Prof. Wiseman
30 hours
Interacting Fields. Time-ordered products. Green functions. Fermion electrodynamics. Interaction picture. Perturbation theory. Asymptotic conditions. Ordering theorems. Wick's theorem. Feynman diagrams. Compton scattering. Electron–electron scattering. Electron–positron annihilation. Cross–sections. Centre–of–mass frame.
Renormalization. Perturbative renormalization of QED to one loop. Regularization. Ward identities. Running couplings.

TP.4 Unification

Prof. Rajantie
27 hours
Introduction. Lagrangian formulation of electrodynamics; Lorentz transformations; gauge invariance; scalar fields.
Global symmetries. Noether's theorem and conservation laws; matrix symmetries; Lie algebras; basic representations.
Local symmetries Covariant derivative; non-Abelian gauge fields.
Spontaneous symmetry breaking. Goldstone's theorem; Higgs mechanism.
Fermion fields. Spinor representations of the Lorentz group; chiral spinors; Dirac equation and spinor field Lagrangians.
The Standard Model. Quantum chromodynamics; electroweak theory; fermion representations; symmetries of the Standard Model; fermion masses.

5 QFFF Course Syllabuses: Optional Courses

TP.5 Advanced Quantum Field Theory

Prof. Tolley
30 hours
Functional Methods. Path integrals in quantum mechanics and quantum field theory. Perturbation theory and Feynman diagrams. Feynman rules from path integrals. Fermions and Grassman variables.
Renormalisation. Ultraviolet divergences and regularisation. Renormalised perturbation theory. Wilsonian renormalisation. Renormalisation group. Callan-Symanzik equation. Dimensional regularisation.
Non-Abelian gauge field theory. Abelian and non-Abelian gauge symmetries. QCD and Yang-Mills theory. Gauge fixing and Faddeev-Popov ghosts. Computation of the beta function. Asymptotic freedom, colour confinement and the continuum limit.

TP.6 Supersymmetry

Prof. Hanany
30 hours
Introduction to supersymmetry. Poincaré algebra, Weyl and Majorana spinors. Grassmann algebra.
N=1 Supersymmetry algebra. Representations of supersymmetry on one-particle states. Extended supersymmetry.
Representation of supersymmetry on component fields. Chiral multiplet. Wess-Zumino model. Supersymmetric generalisation of Maxwell action.
Superspace and superfields. Chiral superfields; superspace form of Wess-Zumino action; superpotential. Scalar superfield and supergauge transformations.
Super Yang-Mills action. Gauge-invariant models of interacting chiral and vector multiplets. Spontaneous supersymmetry breaking.
Advanced topics. Quantum properties of supersymmetric theories. Supergravity. Introduction to supersymmetric Standard Model.

TP.7 Relativity and Cosmology

Prof. Magueijo
30 hours
Relativistic cosmology. The Friedmann-Robertson-Walker metric. Big Bang matter content; Hawking's energy conditions; the cosmological constant. Friedmann equations and their solutions. Observational cosmology. the Hubble diagram. Big Bang puzzles: the horizon problem and Penrose diagrams; the flatness and cosmological constant problems. Alternative cosmologies. anisotropic models. Brans-Dicke cosmologies.
The Hot Big Bang model. Equilibrium and non equilibrium statistical mechanics in expanding Universes; decoupling and freeze-out. Photon decoupling and the cosmic microwave background. Neutrino decoupling. Primordial nucleosynthesis. Relics and dark matter; hot and cold relics. Baryogenesis: Sakharov conditions; a GUT model for baryon asymmetry.

Structure formation. The spherical model. Newtonian perturbation theory. Gauge invariant relativistic perturbation theory. The large scale structure of the Universe. Meszaro effect; Harrisson-Zeldovich initial conditions. The processed power spectrum in Cold and Hot Dark Matter scenarios. Open and Lambda models; high redshift structure formation. The cosmic microwave background: the observational facts; statistical qualifiers; the Sachs-Wolfe formula; the low L plateau; the Doppler peaks.
Inflation. Inflation as a solution to the cosmological puzzles. Slow-roll inflation and model building. Inflation as a theory of structure formation.

TP.8 Black Holes

Prof. Stelle
30 hours

1. The Schwarzschild solution

Gravitational collapse; geodesics; Eddington-Finkelstein coordinates; Kruskal-Szekeres coordinates; Carter-Penrose diagrams; causality, horizons and Cauchy surfaces; singularities and cosmic censorship.

2. Charged and rotating black holes

The Reissner-Nordstrom and Kerr solutions; causal structure; inner horizons; extremal black holes.

3. Killing vectors and Killing horizons

Symmetries and Killing vectors; black hole uniqueness theorems; black hole "no hair" theorems; asymptotic values of energy, momentum and angular momentum.

4. Laws of black hole mechanics

Energy conditions; zeroth, first, second and third laws of black hole mechanics; analogy with thermodynamics; conjectured generalised second law of thermodynamics.

5. Hawking radiation

Quantum Field theory in curved spacetime; complete sets of field modes; Bogoliubov transformations; massless scalar field in a spacetime of a collapsing star; derivation of Hawking radiation; Hawking temperature; black hole entropy and the black hole informa- tion loss "paradox".

6. Advanced Topics

Higher dimensional black holes. Kaluza-Klein theory and the Kaluza-Klein monopole. Pair creation of black holes and topology change.

TP.9 Differential geometry

Prof. Hull
30 hours

Manifolds. The idea of a manifold. Tangent vectors, vector fields and flows. Differential forms and exterior calculus.
Integration, Stokes' Theorem and Cohomology. Integration of differential forms. Stokes' theorem. Cohomology and de Rham's theorem.
Riemannian Geometry. Volume forms and non-coordinate bases. Hodge theory. Connections, covariant differentiation, torsion and curvature. Cartan's structure equations.
Fibre bundles. The idea of a bundle. Vector and principle bundles.

The course will use examples from classical mechanics, quantum mechanics, electromagnetism, general relativity and gauge theory to illustrate these ideas and their application in physics.

TP.11 String theory

Prof. Tseytlin
30 hours
Introduction. Origins of string theory.
Theory of Particles. Covariant action, path integral, relation to quantum field theory, effective action.
Classical String Theory. String actions. Nambu and Polyakov forms.
First-quantised Bosonic String Theory. Conformal invariance, string spectrum, vertex operators.
The Tree-level String S-matrix. Low-energy effective action.
String Perturbation Theory. One-loop amplitudes.
Review of Superstring Theories. Actions, spectrum, effective actions, dualities.

TP.12 The Standard Model and Beyond

Prof. Stelle
30 hours

This course extends the perspective on particle physics up to the current research front, using effective theory methods based on local and rigid symmetries. It is a natural continuation of the perspectives of the Unification and Particle Symmetries courses.
The Standard Model in detail. V-A structure; custodial symmetry; CKM structure; neutrino masses and neutrino oscillations
Discrete and Approximate Symmetries and their Breakdown. CP invariance and violation; effective field theories and their approximate symmetries, chiral symmetry in particular; mathematical structure of nonlinear realisations and its application to nonlinear sigma models with chiral symmetry
Anomalies. Rigid symmetry anomalies and their physical consequences; gauge anomaly cancellation; the theta parameter of QCD; the strong CP problem and axions
Grand Unification and its Difficulties. The Georgi-Glashow Model, $SU(5)$ and $SO(10)$; the evolution of coupling constants; proton decay
Supersymmetry in Particle Physics. Supersymmetric extensions of the Standard Model

Undergraduate Courses

In addition to the above options, students may present at most up to two of the following $3^{rd}/4^{th}$ year undergraduate courses, as need arises, depending on their educational backgrounds:

PHYS96018 Foundations of Quantum Theory
PHYS96019 Group Theory
PHYS97026 General Relativity
PHYS97086 Quantum Theory of Matter
PHYS97080 Quantum Information

All MSc and undergraduate courses are offered subject to staff availability. Both courses and staff change with time and certain courses may not be offered in a given academic year.

Special Topics (non-examinable)

This is a series of short non-examinable lecture courses, given in the summer term weeks following the course examinations by postdocs and staff members, covering areas of recent research interest. They are particularly useful to help MSc students select a topic for their Dissertation.

II. Notes on the MSc Dissertation

All students on the MSc course Quantum Fields and Fundamental Forces are required to submit a Dissertation. The following describes what this involves.

1. Content

Most MSc Dissertations consist of an appraisal of a particular area of currently active research. It is certainly very nice if you can produce some original research although this is rarely possible in the short time available. What the examiners are hoping to see is a critical appreciation of the literature – what has been done, unsolved problems, areas for further research, and so on.

The Imperial Graduate Schools offer courses on technical writing, which students may wish to avail themselves of. For details, see http://www3.imperial.ac.uk/graduateschools.

In reading the Dissertation, the examiners would like to see that you have absorbed and understood the material, and then presented it in your own way. All sources must be properly referenced. A crime that must not be committed is to copy whole sentences or even paragraphs directly from published papers. The examiners reading the Dissertation will probably be more familiar with the literature than you are, and anyone caught doing this will be referred for disciplinary action by Imperial College. The Dissertation must be an independent piece of work. Whilst it is very useful to talk with other students who are writing Dissertations on similar topics, the final piece of work you produce must not be collaborative. Any included text from another source must be properly indicated as a quotation and must be referenced. Serious cases of plagiarism may result in more severe disciplinary action. In this connection, students should consult the College's policy statement on examination offenses: https://www.imperial.ac.uk/student-records-and-data/for-current-students/undergraduate-and-taught-postgraduate/exams-assessments-and-regulations/plagiarism-academic-integrity–exam-offences/

2. Writing the Dissertation

Most of the Dissertation should be written at a high technical level, comparable to published journals, aimed at experts in the field. However, it must in addition include an introductory section aimed much lower, at a general physics audience (so that it could be understood by any MSc student, for example). The introductory section will carry 10 percent of the marks and should be of corresponding length.

The Dissertation should be written in standard scientific style, along the lines of papers published in journals. It should be in good English, although imperfect English is tolerated from students who are not natural English speakers – the most important thing is conceptual clarity. It should also be written with correct spelling. Spell checkers are available on the word processors to assist this.

There exist a number of books describing how a scientific paper or Dissertation should be written. It is a very good idea to spend at least a few hours consulting one of these books before you put pen to paper. See, for example,

- *Writing Successfully in Science*, by Maeve O'Connor (HarperCollins Academic, London, 1991).

- *How to Write and Publish a Scientific Paper*, Third Edition, by Robert A. Day (Cambridge University Press, Cambridge, 1989).

Both these books may be found in the Theory Group book collection, as well as the various College libraries. Professional scientists spend a very large amount of time writing, so it is important to learn this skill as early as possible in one's career.

The length of the Dissertation depends to some extent on the content and subject area. As a rough guide, most Dissertations are between about 50 and 100 pages (double-spaced).

Ideally, the Dissertation should be typed (although this is not absolutely essential). Most students type their own Dissertations, using the word processing facilities available on the group's computer network. The word processing language Latex is now used by almost everyone in theoretical physics, so it is well worth taking the time to learn it. Make sure you budget for a week or so of getting the hang of word processing when organising your time. Standard macros for producing papers are readily available, and these help avoid having to worry about page layout and other similar things.

Citations are important in scientific writing and students should take care to refer to all sources used, and also to present their references in a standard style. It is bad form, for example, to omit page numbers, or to have reference styles change from one citation to the next. No particular referencing style is required, but it should be consistent throughout the Dissertation. Students are encouraged to follow the referencing style of a major journal, such as Phys. Rev. D, Nuclear Physics or JHEP.

The title page of the Dissertation requires only the title, your name, the date, and the statement, "Submitted in partial fulfilment of the requirements for the degree of Master of Science of Imperial College London".

It is not necessary to have the completed Dissertation properly bound, but it is certainly a good idea to put it in some kind of simple binder or folder.

3. How the MSc Dissertation is Marked

The Dissertations are read and given a mark by two staff members, one of whom is usually the Dissertation Advisor. Bear in mind that the other marker may be less expert in the field than the Advisor, so your efforts at making your work comprehensible should be aimed at the less expert one! It is difficult to mark Dissertations in a precise way, but broadly speaking, the marking is broken down into content, presentation and originality:

Content: Has the student fully understood the area covered by the Dissertation? Is it scientifically correct? Is it a thorough account or are key parts missed out? Does it go into the area in sufficient depth? Does the Dissertation bring the reader up to the current frontier of knowledge in that area? (The breadth and depth with which the subject should be covered will vary depending on the area. Equally high marks are possible for covering a narrow area deeply or for giving a broad overview of a much larger area).

Presentation: Is the material described in an organised and coherent fashion? Is there an adequate introduction describing the field in broad and easily accessible terms, and explaining why the subject is useful and interesting? Is there an adequate conclusion, summarising the key aspects of the field and clearly elucidating the areas for further research? Are all the key works in the area adequately referenced? Is the text and its organisation original, or is any of it substantially similar to that of published papers or books?

Originality: As stated above, it is not necessary to do original research, but originality can be expressed through the way the subject matter is penetrated and understood. Is the Dissertation written in an interesting way? Is the subject presented in a way that would be enlightening for experts in the area? Does it indicate connections with other fields that no-one has thought of before? Has the student been able to fill in the missing steps in published accounts of the subject, thereby producing an account of it which goes beyond previous works?

A typical Dissertation will be marked mainly on content, with less emphasis on presentation and originality, but this is by no means rigid, and the examiners have the option of weighting these three aspects at their discretion.

4. Timetable

You should start thinking about the topic of your MSc Dissertation soon after the Easter break. The selection of a topic and of an Advisor for the Dissertation is the responsibility of the individual student. Talk to as many people as you can in order to get ideas for a possible topic. Your Personal Tutor is a good first place to start for general advice, although the person who actually supervises the Dissertation, *i.e.* the Dissertation Advisor, is in general a Staff member whose interests are closest to your chosen topic. PhD students and postdocs are also valuable sources of information. Postdocs may also, subject to approval from the Course Director, serve as Dissertation Advisors. Another useful source of inspiration for MSc subjects is the session of Special Topics lectures, which take place directly after the conclusion of the exams at the end of May. In these lectures, a number of staff members, postdocs and visitors give short courses of lectures on their current research interests.

A title (or at least, a description of the general area of the Dissertation), together with the name of the selected Dissertation Advisor, must be submitted to the MSc Course Director no later than **the last week of June**. Two copies of the completed Dissertation must be handed in to the MSc Course Secretary or the Course Director no later than **the third Friday in September**. At the same time, an electronic pdf copy must be sent to the Course Director.

Note that many staff members are away over the summer. Find out when your Dissertation Advisor is going to be away (see the notice board in the Theory Group Administrator's office) and plan your work accordingly. Make formal arrangements to meet with your Dissertation Advisor at regular intervals throughout the summer. If he/she is going to be away for a substantial period of time, an alternative staff member can be nominated. It is essential that your Advisor see a draft of the Dissertation before it is handed in. A first draft should be available at least **three weeks** before the final deadline.

III. Background Reading for the MSc course

Many students wanting to do the course will have read many popular books on particle physics, black holes etc., and one or two popular books are included below. But it is also important that certain more technical aspects of an undergraduate physics education be properly covered.

The main things students need to know about before starting the QFFF MSc course are as follows:

1. The Lagrangian and Hamiltonian formulation of classical mechanics. This is very important. It is covered in many texts, including quantum mechanics and quantum field theory courses, but a text many students have found useful is,

- T. Kibble and F. Berkshire, Classical Mechanics (Longman, Harlow, 1996).

2. Quantum mechanics to a good undergraduate level. Properties of harmonic oscillators, raising and lower operators, angular momentum, Schrödinger and Heisenberg pictures, identical particles. Some familiarity with scattering theory is also useful. The most important thing is the Dirac notation, which is not always covered in undergraduate courses. Many good books cover this. A simple good undergraduate text is

- P. Davies and D. Betts, Quantum Mechanics, (Chapman and Hall, London, 1994).

3. Some familiarity with Lorentz transformations and tensor notation in special relativity is very useful. The earlier sections in many textbooks in general relativity cover this, as do some books on special relativity. Anyone who has not seen tensors at all, should start with their Newtonian version, Cartesian tensors, which are described in many classical mechanics books. The book

- H.F. Jones, Groups, Representations and Physics (Institute of Physics, Bristol, 1998).

has a short section on tensor notation. The rest of this book, on group theory, serves as a valuable introduction to groups. It is not assumed that students know any group theory at the beginning of the MSc course, but some familiarity will certainly come in very useful.

4. Basic Electromagnetism. The basic properties of Maxwell's equations and its solutions. See, for example,

- E.R. Dobbs, Basic Electromagnetism.

Some books on electromagnetism also cover special relativity and tensors. Volume 2 of the Feynman lectures, for example, is very good on many of these things.

For anyone wanting to read ahead, some texts covering the first term's work on quantum field theory are,

- I.J.R. Aitchison and A.J.G. Hey, Gauge Theories in Particle Physics. Volume 1: From Relativistic Quantum Mechanics to QED (Institute of Physics Publishing, Bristol, 2003).
- F. Mandl and G. Shaw, Quantum Field Theory, Revised Edition (Wiley, Chichester, 1993).

- L.H. Ryder, Quantum Field Theory (Cambridge University Press, Cambridge, 1985).

A low level discussion of quantum electrodynamics is

- R. Feynman, QED: The Strange Theory of Light and Matter (Princeton University Press, 1985; Penguin, 1990).

Two readable accounts of modern particle physics are:

- S. Weinberg, "Dreams of a Final Theory: The Search for the Fundamental Laws of Nature" (Vintage, London, 1993).
- S. Carroll, "The Particle at the End of the Universe" (Oneworld Publications, London, 2012).

IV. General Information about Life in the Theory Group

This section is intended to supply all new arrivals (not just MSc students) with some essential information about the Theory Group and Imperial College.

1. Where to Find Us

Imperial College is located just behind (south of) the Albert Hall in South Kensington. The nearest tube stations are South Kensington, Gloucester Road and High Street Kensington on the Circle Line. South Kensington and Gloucester Road are also on the Piccadilly Line which goes directly to Heathrow Airport. The Theory Group is located in one wing (Rooms 505 – 521) of the fifth floor of the Huxley Building (together with a number of offices on Level 6 above). It may be approached through the Huxley Building, 180 Queens Gate – take the elevator to the fifth floor and turn left along the corridor. Most of the Huxley Building is in fact occupied by the Mathematics and Computer Science Departments, so don't be put off by the signs (or the staff in the front office at the door who have been known to claim there is no Theoretical Physics Group in the building). Alternatively, one may enter through the Blackett Laboratory (where most of the Physics Department is housed) on Prince Consort Road – take the elevator to the fifth floor, turn right, follow the corridor into the Huxley building and then turn left.

2. When you Arrive

MSc & PhD students: please make yourself known to our Theory Group Administrator in room 517 Huxley Building.

3. ID Cards

One of the first things you need to do when you arrive is obtain an identity card. The ID card is essential for a number of purposes, including registering at the Central Library. It is also used as a swipe card to get in and out of the building when the College is locked (at weekends and after 6pm on weekdays). Instructions on how to obtain your ID card will be sent to you directly by the College.

4. General Group Organisation

The Theory Group runs on very limited financial and administrative resources. Mail, telephone calls, fax and photocopying all come directly out of the group budget and should therefore be used only when absolutely necessary and on Theory Group business. We have only one administrator for a group of around one hundred people, including staff, postdocs PhD and MSc students. Also, students are asked not to make unnecessary noise, *e.g.*, by listening to radios. Cooperation is appreciated in all such matters!

5. Whom to See about What

- Head of group – Daniel Waldram
- PhD applications – Andrew Tolley
- MSc applications – Jonathan Halliwell
- MSc Director, timetable and exams – Kelly Stelle
- Theory Group Seminars – Mauro Pieroni and Aaron Held
- Student seminars – Aoibheann Margalit
- Computers – Tim Evans
- Department of Physics Postgraduate Advisor – Arnaud Czaja

6. Seminars

The weekly Theory Group seminars take place on Tuesdays at 1:30 PM in Huxley 503 during term time. There are in addition string theory seminars on Wednesdays at 2:00 PM, cosmology seminars on Fridays at 13:00 and student seminars (given by our PhD students) on Thursdays at 5:00. Announcements about all of these seminars are usually made by email. See also the seminar link on the Theory Group website.

QFFF MSc students are encouraged to attend the Tuesday Theory Group seminars, which aim to give a pedagogical presentation of current research topics.

7. Library Facilities

The group has its own limited collection of books and journals, which are kept in the Theory Group Reading Room, Room 602. Far more extensive collections of books and journals may be found in the Central Library next to the Sherfield Building. This is an amalgam of the Imperial College and Science Museum Libraries. The catalogue may be accessed over the web (starting from the group home page). The Central Library also houses the Haldane Library, with a good general collection (fiction and non-fiction) and a music library.

8. Mail

Our mail address is,Theoretical Physics, Physics Department, Imperial College London, South Kensington campus, London, SW7 2AZ, UK. Mail is delivered twice a day (late morning and early afternoon), to the pigeon holes outside the Theory Group Administrator's office. Outgoing mail (for Theory Group business only) both internal and external, may be left in the trays in the Theory Group Administrator's office, and will be taken down to the mail room before 3:45pm to be posted the same day.

9. Telephones

The Theory Group telephone number is 020 7594 7843, or Ext.47843 internally. The general college number is 020 7589 5111. The College operator may be obtained by dialling 0. Five-figure internal numbers may be dialled directly on the phone in your office. All extension numbers prefixed with a 4 may be dialled directly by external callers using 020 7594-XXXX. Extension numbers prefixed with a 5 do not have the directly dialling facility. Use the College website People Finder on `http://www3.imperial.ac.uk` to find telephone numbers and offices of members of College.

10. Photocopying

Printers/photocopiers may be found in Rooms 516 and 603. These machines also serve as scanners. Students are assigned a certain number of copies/prints that can be made per year. To collect prints, students will need to use their swipe cards in order to enable a printer/copier.

11. Preprints

Preprints can be displayed electronically on the group's homepage, www3.imperial.ac.uk/theoreticalphysics, which also contains a lot of other useful information about the theory group. Please also use this site to see how to automatically assign group preprint numbers. The group's homepage provides easy access to the electronic archives at the Los Alamos National Lab, which is by now the most widely used method of circulating preprints, and also some of the journals (such as Physical Review) which are now available electronically. The College library homepage has a complete list of the electronic journals to which we have access.

12. General Facilities

There are printer/copiers in Rooms H516 and H603, which are enabled using your College Identification/swipe card. Incoming mail to MSc students arrives in the mailbox immediately outside the Theory Group Administrator's office. See Section IV for more details on all practical matters.

13. Security and Emergencies

Emergencies of all types may be reported to Ext.4444. There is a First Aid box in the Theory Group Administrator's office.

Petty theft from offices happens from time to time. Don't leave valuables lying around and *always* close and lock the door to your office, even if you go out for just a short time.

More seriously, there have recently been a number of cases of large-scale computer theft from Imperial College, at least one of which was from the Huxley building. Make sure that the doors to any rooms containing computers are properly locked if you are one of the last to leave in the evenings or at weekends. Unfortunately, some thefts have been from locked offices, so if you have a laptop, either take it home each night or lock it in a secure place. If you see any unfamiliar characters wandering around in the evening or at the weekend, ask who they are and what they are doing. If you are at all suspicious call security at the above number.

14. Students with Disabilities

Imperial College London has a comprehensive policy of assistance to students with disabilities. Details may be found in the College document to be found at
http://www3.imperial.ac.uk/disabilityadvisoryservice/supportforstudents/disabilitystatement

15. Bookshops

There are numerous bookshops in London. Shops likely to have books of interest are the Waterstones branch at 82 Gower Street, Foyles, at 119 Charing Cross Road, and Blackwells, also on Charing Cross Road. Try also Amazon books, at www.amazon.co.uk.

16. Accommodation

If you are new to London, you could easily take a good week or two finding somewhere to live. The College has a number of offices which may provide you with help in finding accommodation. Short-term accommodation, either in the form of a College guest room or a local hotel, may be booked through the College Conference Office. For long-term accommodation, students should go to the Accommodation Office at 15 Prince's Gardens (Ext.5-9444, 5-9445, 5-9446 or from outside, 0207 594 9444). Other long-term visitors should go to HUB, at 355 Sherfield (Ext.4-8741). Outside the College, two of the most useful sources of listings are *The Evening Standard* and *Loot*, both published on six days of the week.

17. Food and Drink

Many members of the group take lunch in the Senior Common Room, on the Level 2 of the Sherfield Building. Similar food (slightly cheaper) is available next door in the Student Common Room, or downstairs in the Main Dining Room.

Tea, coffee and sandwiches are available in the Physics Common Room, on Level 8 of the Blackett Lab (which also offers an impressive view over London). Due to their large number, MSc students are unfortunately not permitted to use the Maths Department Common Room on Level 5 of the Huxley Building.

One of the highlights of life in the theory group is the Lavazza espresso machine, currently in the photocopy room, which all members of the group are encouraged to use. Coffee for the machine comes in small pods (see instructions by the machine for who to buy these from). The pods cost 85p each. Please buy in bulk.

A number of restaurants and pubs, at a range of prices, may be found on Gloucester Road (one block west of Queen's Gate), and around the tube station at South Kensington. (See the Local Restaurant Guide on the home page). Beit Quad and Southside have student bars.

18. Health

The College Health Service may be found at Southside, Watt's Way, Prince's Gardens. Their telephone number is Ext.4-9375. For emergencies call Ext.4444. Students, local residents and visitors from overseas may all use the Health Service free of charge. The Health Service is open

from 8:30am to 6pm during term time, 8:30am to 5pm out of term (closed at lunch time from 12 – 1). Appointments may be made by calling the above number. Otherwise, there is an open clinic (appointments not necessary) from 8:30am to 10am, Monday to Friday. In addition to General Practitioners, an extensive range of services are offered, including free condoms, physiotherapy, acupuncture, herbal medicine, osteopathy, massage, psychotherapy, vaccinations and treatment for sports injuries. Dental treatment is also provided at the Health Service. It is open from 9am to 6pm. Appointments are usually necessary (call 0207 589 6623 or Ext.4-9396). It is generally necessary to pay for dental treatment, although students and those on income support can obtain subsidies.

19. Sports Facilities

After a hard day pushing back the frontiers of knowledge, you are probably ready to take out your frustrations on a squash ball, or partake of some other such vigorous activity. The College Sports Centre has a number of facilities for this purpose. It is open to anyone (although it is cheaper for members of the College with a valid ID card).

Details of the facilities and opening times can be found at `http://www3.imperial.ac.uk/sports`.

20. Banking

Students and long-term visitors will doubtless find it useful to open a bank account in London. The four largest banks in the UK are National Westminster, Barclays, Lloyds-TSB and HSBC, all of which have branches in South Kensington. There is an office of Santander in the College walkway. Many banks are attentive to the special needs of students. Students from abroad should bring their passport and a Certificate of Registration at Imperial College when opening an account A cheque book will be issued as soon as funds are paid into a new account. Issue of a cheque guarantee card and cashline card (often combined into a single card) requires an initial deposit and may be issued only after an initial period. Bring as much useful information as you can, *e.g.*, visitors from abroad should bring bank statements. British banks are not always very receptive to visitors from abroad who wish to open accounts, so some patience may be required.

21. Travel and absences

All staff and students travelling on College business are covered by the College's insurance policy. It is necessary, however, to register all overseas trips with the Insurance Office beforehand. Information, links for trip registration and a copy of the cover note are to be found at:

https://wiki.imperial.ac.uk/display/FKB/Overseas+travel

If you plan to be absent from lectures for more than three days, you should inform the Theoretical Physics Group administrator, Ms Graziela DeNadai (g.denadai@imperial.ac.uk). This is particularly important should you fall ill. If you are travelling away from London, you should indicate how you may be contacted and how long you will be gone for.

22. Life in London

Time Out, a free magazine and associated web site, has listings of much that is going in London.

The Guardian newspaper on Saturday also has listings, which is not as comprehensive.

23. Moving on from Imperial

Many students who successfully complete the MSc go on to do a PhD. The number of positions available here in the Theory Group is very small, but there are many other institutions in the UK which are very willing to take on graduates from the MSc course. A distinction is usually needed to go on to do a PhD in theoretical particle physics, but a PhD in other areas may be possible with a good pass. You should start thinking about submitting applications in January. PhD interviews around the country typically take place from February onwards. See the group webpage for more information about PhD applications.

24. And When You Leave ...

Make sure you return all keys, copy cards, ID card, books *etc.* For advice on applying for PhDs, students should consult with their Personal Tutors. Start thinking about this already in the autumn term.

V. Computer Facilities

General support and information

An Imperial computing account is required for any activity on the college computer network. This should be set up automatically and will be available a short time after you arrive. Computers which are not on a desk belonging to a particular individual member of the group are available for general use. In particular those PCs in the computing room H514 may be used by anyone in the group. In addition there are BW duplex laser printers on each floor and one PC in the computing room has a scanner attached. There is in addition a colour printer on level 6. Personal laptops may also be used but wireless coverage is very limited in the group and not all wall sockets are enabled. For more details see the computing notes on the group web site under `Intranet` → `Group Computing` or look at the ICT (Information and Communication Technologies division) web pages `http://www3.imperial.ac.uk/ict/` which may well have answers to your questions.

VI. Appendix: College Notices

There are many general aspects of life and study at Imperial College which are common to all Departments and postgraduate study programmes. Information on these general aspects and specific College notices are covered in the separate Student Handbook Appendix.