Quantum Theory

[PHYS11019]

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- Lectures:
  Tuesday 9:00-9:50 LTC
  Friday 9:00-9:50 LTC
  - additional lecture: wk1 Thursday [18/09/24] 16:10-17:00 LTC (no workshop)
- Workshops: Thursday 16:10-18:00 LTC
  TA: Shen Yan

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Contents

Synopsis

In this course we will review the fundamental ideas of quantum mechanics, introduce the path integral for a non-relativistic point particle, and use it to derive time dependent perturbation theory, the Born series for nonrelativistic scattering, and Feynman perturbation theory. The course ends with an introduction to relativistic quantum mechanics and some of the ideas of quantum field theory.

Prior attendance at an undergraduate course on quantum mechanics is assumed. Prior attendance at courses on Lagrangian Dynamics and Complex Analysis are strongly recommended. Quantum Theory complements the Level 10 Quantum Physics course, but is more advanced.

Syllabus

(I) Quantum kinematics: slit experiments, Hilbert space, Dirac notation, complete sets of states, operators and observables, space as a continuum, wave number and momentum.

(II) Time evolution: the amplitude for a path, the Feynman path integral, relation to the classical equations of motion and the Hamilton-Jacobi equations.

(III) Evaluating the path integral for the free particle and the harmonic oscillator. Derivation of the Schrödinger equation from the path integral. The Schrödinger and Heisenberg pictures for time dependence in quantum mechanics. The transition amplitude as a Green function. Picking out the ground state. Charged particle in an EM field, Aharonov-Bohm effect, Transition elements, Ehrenfest's Theorem and Zitterbewegung.

(IV) Time-dependent perturbation theory using path integrals: time ordering and the Dyson series, perturbative scattering theory, the Born series, differential cross-sections, the operator formulation, time dependent transitions.

(V) Feynman perturbation theory and Feynman diagrams. Green functions.

(VI) Relativistic quantum theory: the Klein-Gordon and Dirac equations. Negative energy solutions, spin, necessity for a many particle interpretation. Nonrelativistic limit of the Dirac equation in an electromagnetic field.

Workshops, Exam and Notes

Working through problems is the best way to learn and understand mathematical physics in general, and this course in particular. Therefore, there are ten two-hour workshops throughout the term with accompanying tutorial sheets of problems. Students should look at these beforehand in order to get help on the parts they find difficult during the workshop. Written solutions to the problems will be provided, but not immediately. It is essential that students try the problems independently before looking at the solutions; otherwise the value of doing the problems is lost.

The exam for this course will be at the end of the academic year in **April/May** unless you are a visiting student only for the first semester. There will be a revision session after Easter.

These notes are based heavily on a previous version by Jenni Smillie and Brian Pendleton, which in turn were based on notes from Richard Ball, and I am very grateful for this resource. Any errors are of course my own responsibility.

Please email any comments, questions or corrections to **rhorsley@ph.ed.ac.uk**

Recommended Textbooks

These notes are intended to be self-contained, but you may find the following textbooks useful:

- "Quantum Mechanics and Path Integrals" by R. P. Feynman and A. R. Hibbs, emended by D. F. Styer (Dover Publications)

  The classic book by the founder of Path Integrals. Feynman has unique insights into physics and good explanations although you may find it rather wordy.

- Many texts on 'Quantum Field Theory' have an introductory chapter on path integrals, for example

  "Field Theory, A path integral approach" by A. Das

  The first ~ 100 pages are relevant.

- "Path Integral Methods and Applications" by R. MacKenzie,

  arXiv:quant-ph/0004090

- "Principles of Quantum Mechanics" by R. Shankar

  A good general QM book; some discussion of path integrals and the Dirac equation.

- "Introduction to Quantum Mechanics" by D. J. Griffiths

  A good general QM book; but no discussion of path integrals.

Some more advanced texts are:

- "Path Integrals in Quantum Mechanics" by J. Zinn-Justin

  Advanced material.

- "Path Integrals in Quantum Mechanics, Statistics, Polymer Physics and Financial Markets" by H. Kleinert

  Encyclopedic – more than you will ever need to know.

The library classification code for this topic is QC174. If there are other textbooks which you find particularly helpful, please email me and I will update the list.

Formulations of Quantum Mechanics

Quantum Mechanics started with two ostensibly different formulations, both based on the Hamiltonian:

(1925) Heisenberg, Born and Jordan: Matrix Mechanics

(1925) Schrödinger: Wave Mechanics

These were shown to be equivalent by Dirac and Schrödinger in 1926

(1942) Feynman: Path Integral or Sum over Histories

Feynman's formulation is based on the Lagrangian and is ideal for scattering and time-dependent problems and (especially) for relativistic and many-particle systems. Unfortunately bound-state problems are generally harder to solve using paths integrals (as we shall see).