

# The Standard Model

Part of the University of London post-graduate lectures in high-energy physics

Matthew Wing (UCL), 2008/9

## Detailed syllabus

### 1 Introduction: matter and forces (4 hours)

- Matter content of the Universe
- Forces
  - Gravity
  - The weak force
  - Electromagnetism
  - The strong force
- Concepts of local gauge invariance, gauge interactions and symmetry breaking
- Grand unified theories

TOTAL: 4 hours

### 2 Experimental concepts (1 hours)

- Experimental possibilities
- Cross section
- Luminosity
- Natural units and conversion factors
- What happens to particles in matter

TOTAL: 5 hours

### 3 Experiments of the last 50 years (4 hours)

- Bubble chambers
- Mesons and baryons
- Neutrino experiments
- High-energy colliding beam experiments: early  $e^+e^-$  and  $pp$ , LEP, HERA, Tevatron, future

TOTAL: 9 hours

## 4 Non-relativistic quantum mechanics (4 hours)

- Schrödinger's equation and probability current
- Heisenberg and interaction picture
- Harmonic oscillator using Dirac operators
- An-harmonic oscillator and Rayleigh-Schrödinger perturbation theory
- The Lagrangian
- The Dirac delta function
- The Heaviside unit step function

TOTAL: 13 hours

## 5 Special relativity (1 hour)

- Quick introduction: four-vectors, Lorentz transformation, light cone
- Relativistic kinematics, centre-of-mass energy, Mandelstam variables

TOTAL: 14 hours

## 6 Relativistic spin-0 particles (1 hour)

- The Klein-Gordon equation
- Perceived problem in the Klein-Gordon equation
- Feynman-Stückelberg interpretation of negative energy solutions

TOTAL: 15 hours

## 7 Calculating amplitudes (1 hour)

- Possible approaches
- Propagator approach

TOTAL: 16 hours

## 8 Spinless $e^-\mu^-$ scattering (3 hours)

- Electrodynamics of spinless particles
- Definition of the cross section
- Number of final states
- Flux factor
- Cross section evaluation

TOTAL: 19 hours

## 9 Relativistic spin-1/2 particles (5 hours)

- Non-relativistic description. Pauli matrices, commutation relations, rotations in 3D, SU(2)
- The Dirac equation,  $\alpha$  and  $\beta$  matrices and  $\gamma$  matrices
- The adjoint Dirac equation and the conserved probability current
- Solutions of the Dirac equation
- Orthogonality and normalisation
- Spin,  $\gamma^5$  and helicity
- Completeness relation
- Possible forms of interaction in the Dirac theory

TOTAL: 24 hours

## 10 $e^-\mu^-$ scattering (3 hours)

- Electron in an EM field
- Trace theorems
- $d\sigma/d\Omega$  for the process

TOTAL: 27 hours

## 11 $e^+e^-$ annihilation to $\mu^+\mu^-$ (2 hours)

- Obtain from above scattering result
- R at  $e^+e^-$  colliders
- Helicity conservation at high energies

TOTAL: 29 hours

## 12 Massless spin-1 particle – the photon (3 hours)

- Maxwell's equations and definition of the classical potential
- Lorentz condition and gauge transformation
- Virtual photons and the photon propagator
- Real & virtual photons and significance of longitudinal and time-like photons

TOTAL: 32 hours

## 13 Massive spin-1 particles (2 hours)

- The Proca equation
- Polarization vectors
- Propagator for virtual vector bosons
- Propagator for unstable virtual vector bosons

TOTAL: 34 hours

## 14 Compton scattering (2 hours)

TOTAL: 36 hours

## 15 Charge current weak interactions (6 hours)

- Introduction
- Relation between  $G_F$  and  $g_w$
- Leptonic CC processes,  $\nu e^-$  scattering
- $O(n)$ ,  $U(n)$  and  $SU(n)$
- CKM matrix
- $\nu q$  scattering
- $\pi/K$  decay to  $e/\mu$
- Calculation of  $W$  width

TOTAL: 42 hours

## 16 Neutral current weak interactions (2 hours)

- Weinberg-Salam model
- Neutral current processes
- $Z^0$  peak

TOTAL: 44 hours

## 17 QCD (3 hours)

- Deep inelastic scattering
- Quark-parton model
- Drell-Yan process
- Evolution of the structure functions

TOTAL: 47 hours

## 18 Local Gauge Invariance and determination of the form of interaction (3 hours)

- Local gauge invariance of the EM field
- Local gauge invariance and the electroweak interaction
- Trilinear and Quadrilinear couplings
- Local gauge invariance and QCD
- Evolution of the coupling constants

TOTAL: 50 hours

## 19 Spontaneous symmetry breaking (4 hours)

- Some models
- Weinberg model
- Masses of  $W$  and  $Z$
- Coupling to  $W$  and  $Z$
- Fermion masses
- Mass matrices and the KM matrix
- Cosmological problem
- Lagrangian of the Standard Model

TOTAL: 54 hours

## 20 Beyond the Standard Model (2 hours)

- Grand Unified Theories

TOTAL: 56 hours

## Recommended books

- I.J.R. Aitchison and A.J.G Hey, “Gauge theories in particle physics”, Vols. I and II, IoP publishing, 3rd Ed. (2003).
- F. Halzen and A.D. Martin, “Quarks and leptons: an introductory course in modern particle physics”, Wiley (1984).
- D.M. Gingrich, “Practical Quantum Electrodynamics”, Taylor and Francis (2006).

## Other useful texts

- R.K. Ellis, W.J. Stirling and B.R. Webber, “QCD and collider physics”, Cambridge (1996).
- E.A. Paschos, “Electroweak Theory”, Cambridge (2007).
- B.R. Martin and G. Shaw, “Particle physics”, Wiley (1992).
- W.S.C. Williams, “Nuclear and particle physics”, Oxford (1991).
- S. Eidelman et al., “Review of particle physics”, Physics Letters **B 592** (2004) 1.
- J.D. Bjorken and S.D. Drell, “Relativistic Quantum Mechanics”, McGraw (1964).
- e.g. G. Arfken, “Mathematical Methods for Physicists”, Academic Press (1985).