Subatomic Physics: Particle Physics Study Guide

This is a guide of what to revise for the exam. The other material we covered in the course may appear in questions but it will always be provided if required. Remember that, in an exam, the masses of the particles are provided on the constant sheet.

At the end of this summary a list of the equations you need to remember, and a summary of the forces and Feynman rules.

Quarks, Leptons and Quantum Numbers

- The quarks and leptons (a.k.a. the fermions) and their anti-particles. Which fermions interact under which forces.
- The definition of the following quantum numbers - and if they conserved or not due to interactions with the different forces:
  - Electric charge, Q.
  - Total quark number, N_q.
  - Lepton numbers: L_e, L_μ, L_τ
  - The individual quark flavour quantum numbers: N_u, N_d, N_s, N_c, N_b, N_t.
  - Colour charge, in so far as the quarks always carry a colour charge, there are three colour charges, and the net colour charge is conserved.

Forces

There is a summary of the forces at the end of this guide.

- The three forces we have to consider in particle physics: strong, electromagnetic and weak; which bosons propagate the forces.
- The coupling constants (in symbols for photon, gluon and W-boson interactions); the relative strength of the forces.
- The allowed flavour changes for W-boson interactions. (The flavour of the quarks and leptons is conserved in interactions with the other bosons.)
- The idea of the Yukawa potential, in so much as that the exchange of bosons can described mathematically through an effective potential.
- The idea that the coupling constants change as a function of the boson momentum.
- The idea that real W and Z bosons can be produced in colliders if $\underline{\underline{q}}_W \sim m_W, \underline{\underline{q}}_Z \sim m_Z$ and then W and Z boson properties can be directly studied (such as decay width, decay modes, branching ratios etc).

Scattering and Decay

These are the two main processes we can measure in particle physics to investigate the properties of the fermions and the interactions. You should revise:

- Elastic collision and inelastic collisions.
- Rough lifetimes for decays due to the different forces.
- Which particles don't decay, and why.
- The definition of total width for a particle (equation (5)). The definition of partial width and branching ratio for a decay (equations (7) and (6)).
- What conditions must be satisfied for decays to occur.

Particle Physics Experiments and Detectors

- The definition of the Lorentz invariant quantity s, equation (4).
- The definition of the effective centre-of-mass energy, $\sqrt{\hat{s}}$.
- The concepts of fixed target experiments and collider experiments. Why colliders are better at producing high mass particles.
- What a synchrotron and a linear accelerator (linac) are. How particles in these accelerators are accelerated. Which particles are usually used in collider experiments.
- What synchrotron radiation is.
- For long-lived particles - ones that live long enough to reach a detector ($L = \beta\gamma c\tau >\sim$ 1 cm) - such as electrons, muons and photons:
  - How these particles with interact with matter.
  - How these particles appear in a detector, such as the ATLAS detector.
- Quark signals in a detector *i.e.* hadronisation.
- Neutrino signals in a detector *i.e.* missing momentum balance in the direction transverse to the beams.

Hadrons

- What hadrons, mesons and baryons are, and why quarks are confined to hadrons.
- What a parton is, the consequences of the parton model, and definition of the associated quantity x. What the measured distribution of partons in the proton is.
- The evidence for gluons.

Relativistic Dynamics

- Conservation of four-momentum! This is especially important for calculating the boson four momentum, $\underline{\underline{q}}$, in the boson propagator terms, and in decays and scattering.

Natural Units

- We set $\hbar = c = 1$. The most important implication of this is that mass, momentum and energy are all measured in units of energy, usually MeV or GeV.

Feynman Diagrams and Feynman Rules

- How to draw simple Feynman diagrams.
- How to calculate the matrix element $\mathcal{M}$ for simple means diagrams with just one boson.
- How to relate $\mathcal{M}$ to the cross sections, σ, (equation (9)) and partial decay widths, Γ (equation (7)).

Concepts

- What is anti-matter, how it is related to the matter particles, and how we can interpret anti-matter.

Equations

This is a list of equations you need to know! Note some of the equations use specific collisions and decays as examples; the equations, however, apply to all types of collisions and decays.

- The four momentum of a particle, in natural units is:

$$\underline{\underline{p}} = (E, p_x, p_y, p_z) = (E, \vec{p}) \tag{1}$$

  where E is the energy, and $\vec{p}$ is the three momentum.

- The square of the four momentum of any *initial* or *final state* particle is its mass squared:

$$\underline{\underline{p}}^2 = E^2 - \vec{p}\cdot\vec{p} = m^2 \tag{2}$$

  This is not necessarily true for intermediate particles such as bosons propagating an interaction: if $\underline{\underline{q}}^2_{\text{boson}} \neq m^2_{\text{boson}}$ we say the boson is *virtual.*

- The Lorentz Transformations in natural units are:

$$\gamma = E/m \;\Rightarrow\; E = \gamma m \qquad \beta = |\vec{p}|/E \qquad \gamma\beta = |\vec{p}|/m \tag{3}$$

- In a collision (at a collider or fixed target) the centre of mass energy is $\sqrt{s}$, where s is the square of the sum of the four-momentum of the colliding particles. *e.g.* for an $e^+ - e^-$ collision:

$$s = (\underline{\underline{p}}_{e^+} + \underline{\underline{p}}_{e^-})^2 \tag{4}$$

- The total width of a particle (Γ) and the lifetime of the particle (τ) are related as:

$$\Gamma = \hbar/\tau \tag{5}$$

- The branching ratios of a decay is, *e.g.*:

$$\text{BR}(K^0 \to \pi^+\pi^-) = \frac{\Gamma(K^0 \to \pi^+\pi^-)}{\Gamma_{K^0}} \tag{6}$$

  where $\Gamma(K^0 \to \pi^+\pi^-)$ is the width of individual decay $K^0 \to \pi^+\pi^-$.

- The width of individual decay modes (called partial widths) are proportional to $\mathcal{M}^2$, *e.g.*

$$\Gamma(K^0 \to \pi^+\pi^-) \propto \left(\mathcal{M}(K^0 \to \pi^+\pi^-)\right)^2 \tag{7}$$

  The total width of a particle is the sum of the partial width of all possible decay modes:

$$\Gamma_{K^0} = \Gamma(K^0 \to \pi^+\pi^-) + \Gamma(K^0 \to \pi^0\pi^0) \tag{8}$$

- The cross section, σ, of a scattering is proportional to the matrix element squared: $\mathcal{M}^2$, *e.g.*

$$\sigma(e^+e^- \to \mu^+\mu^-) \propto \left(\mathcal{M}(e^+e^- \to \mu^+\mu^-)\right)^2 \tag{9}$$

What you don't have to remember

If you need any of these, they will be given!

- The masses of all the particles; in an exam they are given on the constant sheet.
- The lifetimes of all the particles.
- The quark content of all the hadrons.
- The names of the accelerators and experiments, which particles and energies they use.

QED	QCD	Weak Neutral Current	Weak Charged Current
quantum theory of EM interactions	quantum theory of strong interactions	quantum theory of weak interactions	
mediated by exchange of virtual photons	mediated by exchange of gluons	mediated by exchange of Z bosons	mediated by exchange of W bosons
acts on all charged particles	acts on quarks only	acts on **all** quarks and leptons	
couples to electric charge	couples to colour charge	does not change quark or lepton flavour	changes quark and leptons flavours
coupling strength $\propto$ fermion charge $\propto e \propto \sqrt{\alpha}$	coupling strength $\propto g_S \propto \sqrt{\alpha_S}$ (equal for all quark flavours)	coupling strength $\propto g'_W$	coupling strength $\propto g_W \propto \sqrt{\alpha_W}$ at lepton vertex: g_w at quark vertex: $g_w V_{qq'}$
photon propagator: $1/\underline{\underline{q}}^2$	gluon propagator: $1/\underline{\underline{q}}^2$	Z-boson propagator: $1/(\underline{\underline{q}}^2 - m_Z^2)$	W-boson propagator: $1/(\underline{\underline{q}}^2 - m_W^2)$