Physical Constants

Permittivity of free space	ε_0	=	8.854×10^{-12}	$\mathrm{F\,m^{-1}}$
Permeability of free space	μ_0	=	$4\pi \times 10^{-7}$	$\mathrm{H\,m^{-1}}$
Speed of light in free space	c	=	2.998×10^{8}	$\mathrm{m\,s^{-1}}$
Gravitational constant	G	=	6.673×10^{-11}	$\mathrm{N\,m^{2}\,kg^{-2}}$
Elementary charge	e	=	1.602×10^{-19}	C
Electron rest mass	m_{e}	=	9.109×10^{-31}	kg
Unified atomic mass unit	m_{u}	=	1.661×10^{-27}	kg
Proton rest mass	m_{p}	=	1.673×10^{-27}	kg
Neutron rest mass	m_{n}	=	1.675×10^{-27}	kg
Planck constant	h	=	6.626×10^{-34}	$\mathrm{J\,s}$
Boltzmann constant	k_{B}	=	1.381×10^{-23}	$\mathrm{J\,K^{-1}}$
Stefan-Boltzmann constant	σ	=	5.670×10^{-8}	$\mathrm{W\,m^{-2}\,K^{-4}}$
Gas constant	R	=	8.314	$\mathrm{J\,mol^{-1}\,K^{-1}}$
Avogadro constant	N_{A}	=	6.022×10^{23}	$\mathrm{mol^{-1}}$
Molar volume of ideal gas at STP		=	2.241×10^{-2}	$\mathrm{m^{3}}$
One standard atmosphere	P_0	=	1.013×10^{5}	$\mathrm{N\,m^{-2}}$
$1\,\mathrm{MeV\,c^{-2}}$		=	1.783×10^{-30}	kg
Muon rest mass	m_{μ}	=	105.660	$\mathrm{MeV\,c^{-2}}$
Pion rest mass	m_{π}	=	139.568	$\mathrm{MeV\,c^{-2}}$
Top quark rest mass	m_{t}	$\approx$	175	$\mathrm{GeV\,c^{-2}}$
Reduced Planck constant	$\hbar$	=	$h/2\pi$	

SECTION A – Answer SIX parts of this section

1.1) Which of the following reactions are allowed to proceed by way of the weak interaction?

(i) $\nu_e + p \to e^+ + n$
(ii) $\nu_\mu + n \to \mu^- + \pi^0 + p$
(iii) $\Sigma^- \to \pi^0 + e^- + \bar{\nu}_e$
(iv) $K^0 \to \pi^+ + e^- + \bar{\nu}_e$.

Give a reason for each reaction which is forbidden.

[7 marks]

1.2) State which force is most likely to mediate the following processes:

(i) $e^- + p \to \nu_e + n$
(ii) $e^- + e^- \to e^- + e^-$
(iii) $\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-$
(iv) $e^+ + e^- \to \nu_\mu + \bar{\nu}_\mu$.

Draw an appropriate Feynman diagram in each case.

[7 marks]

1.3) A charged pion decays at rest into a muon and a neutrino. The energy of the muon is measured to be *at least* 109.450 MeV. Show that the rest mass of the neutrino is $m_\nu \leq 9.583\,\mathrm{MeV\,c^{-2}}$.

[7 marks]

1.4) Write down one example of the associated production of strange particles which occurs when a proton beam is made to collide with a solid target. Which force is involved in this process? By which force do most strange particles decay? Write down one example of this, and one example of a strange particle decay mediated by a different force.

[7 marks]

1.5) Write down the main processes by which neutrinos are produced in the upper atmosphere following the interactions of primary cosmic rays. Explain why you would expect approximately twice as many muon neutrinos (ν_μ) as electron neutrinos (ν_e) to be produced. State a possible reason why the relative detection rate ν_μ/ν_e in a ground based detector is not equal to two.

[7 marks]

1.6) What are the principal components of a modern particle accelerator? In such machines, why are the particles accelerated in bunches?

[7 marks]

1.7) What are the symmetries related to the conservation of energy, momentum and angular momentum? Show that the parity operation is analogous to a mirror reflection followed by a rotation. Why is it possible to neglect the rotation in this analogy when considering the effect of the parity operation on a system?

[7 marks]

1.8) Show, by use of an appropriate diagram, how *phase stability* leads to bunching of charged particles in a cyclic accelerator such as a synchrotron.

[7 marks]

SECTION B – Answer TWO questions

2) a) What is meant by (i) the four-momentum of a particle, (ii) a conserved quantity and (iii) an invariant quantity? Give one example of a conserved quantity and one of an invariant quantity.

[8 marks]

b) Define the system of natural units. Hence obtain values, in SI units, for the natural units of length, energy and time.

[6 marks]

c) Show that when a particle of mass m collides with a stationary particle of mass M, the minimum energy required to produce a state of mass M* is, in natural units,

$$E_{\text{threshold}} = \left(M^{*2} - M^2 - m^2\right) / 2M \,.$$

[6 marks]

d) Determine the threshold energy for producing a meson containing the top and anti-top quarks when beams of equal energy electrons and positrons are made to collide head on.

[3 marks]

e) It is proposed to produce the same meson as in part (d) by using a beam of electrons incident on a stationary proton target. Determine the electron energy needed and comment on the feasibility of this experiment.

[7 marks]

3) a) Yukawa postulated that the strong nuclear force, between protons and neutrons, was mediated by the exchange of particles. Given that the strong nuclear force was known to have a range of about 10^{-15} m, estimate the mass, in MeVc^{-2}, of Yukawa's postulated particle.

[2 marks]

b) By considering possible interactions between protons and neutrons, determine the minimum number of charge states of Yukawa's particle.

[6 marks]

c) It is now thought that the strong nuclear force is not fundamental, but it is the external manifestation of the strong force between quarks. Explain why the interquark force is of finite range but appears to be carried by massless exchange particles (gluons).

[5 marks]

d) By considering that the strong force between quarks is due to the exchange of the quantum number colour, explain why there are eight independent gluons.

[5 marks]

e) Exchange particles are now called gauge bosons. Explain why, in Grand Unified Theories (GUTs), gauge bosons with masses $\sim 10^{16}\,\text{GeV}\,c^{-2}$ are needed. Draw a quark Feynman diagram showing how these gauge bosons could lead to proton decay.

[7 marks]

f) Briefly discuss experiments carried out to try to observe proton decay. What implications for GUTs do the results have?

[5 marks]

4) a) Write down the general quark structures of baryons and mesons.

[2 marks]

b) State why the quark structures of some baryons caused an initial problem with the quark model, and describe how this problem was overcome by the introduction of the quantum number *colour*.

[4 marks]

c) Briefly describe the experiment in which the bottom quark was discovered. Why did the subsequent discovery of the top quark entail a much more difficult experiment?

[6 marks]

For the remaining parts of this question you may find the table at the end of the question helpful.

d) Five observed hadrons have the following quantum numbers (Q, B, S, C, $\underline{B}$, T):

(i) (−1, +1, −3, 0, 0, 0)
(ii) (+1, +1, −1, +1, 0, 0)
(iii) (0, 0, 0, −1, 0, 0)
(iv) (0, +1, 0, 0, −1, 0)
(v) (0, −1, +2, 0, 0, 0).

Identify the quark constituents of each of these hadrons, explaining your reasoning.

[10 marks]

e) Determine which of the following hadron states, with quantum numbers (Q, B, S, C, $\underline{B}$, T), are compatible with the quark model and which are not:

(i) (+2, +1, 0, 0, 0, +1)
(ii) (−1, +1, 0, 0, 0, +1)
(iii) (0, 0, 0, −1, 0,+1)
(iv) (+1, 0, +1, 0, 0, −1).

[8 marks]

Name & symbol	Electric charge Q	Baryon number B	Strangeness S	Charm C	Bottomness $\underline{B}$	Topness T
Down, d	$-1/3$	$+1/3$	0	0	0	0
Up, u	$+2/3$	$+1/3$	0	0	0	0
Strange, s	$-1/3$	$+1/3$	−1	0	0	0
Charmed, c	$+2/3$	$+1/3$	0	+1	0	0
Bottom, b	$-1/3$	$+1/3$	0	0	−1	0
Top, t	$+2/3$	$+1/3$	0	0	0	+1

5) a) List five key features of each of the following experiments:

(i) NuTeV, which measured the electroweak mixing parameter $\sin^2\theta_W$;

[5 marks]

(ii) the Relativistic Heavy Ion Collider (RHIC) experiment, in which a signature corresponding to the postulated quark-gluon plasma was seen;

[5 marks]

(iii) Belle, in which the production of a new type of meson was observed.

[5 marks]

b) Discuss the significance of the results of each of these experiments. Which of the results is, in your opinion, the most significant? Back up your claim with as many arguments **for** your choice and **against** the other two as you can.

[15 marks]