King's College London

UNIVERSITY OF LONDON

B.Sc. EXAMINATION

CP/3240 Theoretical nuclear and particle physics

Summer 1999

Time allowed: THREE Hours

Candidates must answer SIX parts of SECTION A, and TWO questions from SECTION B.

Separate answer books must be used for each Section of the paper.

The approximate mark for each part of a question is indicated in square brackets.

You must not use your own calculator for this paper.
Where necessary, a College Calculator will have been supplied.

TURN OVER WHEN INSTRUCTED

Rest mass of W boson $m_W \approx 80\,\text{GeV}\,c^{-2}$

Reduced Planck constant $\hbar = 1.055\times10^{-34}\,\text{J s}$

Speed of light $c = 2.998\times10^{8}\,\text{m s}^{-1}$

Electron volt, $1\,\text{eV} = 1.602\times10^{-19}\,\text{J}$

SECTION A. Answer any **SIX** parts of this section.

1.1 Which property defines whether a particle is a *hadron* or a *lepton*? State which type of particle each of the following are: electron, proton, neutrino, pion, up-quark.

[7 marks]

1.2 Why is the range of the electromagnetic interaction infinite, whereas that of the weak interaction is finite? Estimate the range of the weak interaction.

[7 marks]

1.3 Use an analogy with ferromagnetism to describe the phenomenon of *spontaneous symmetry breaking*. How is spontaneous symmetry breaking thought to be connected with particle masses?

[7 marks]

1.4 All of the following interactions are allowed to take place. State *all* the forces — strong, electromagnetic or weak — which could be responsible in each case.

(i) $e^+ + e^- \to e^+ + e^-$

(ii) $\bar{\nu}_e + e^- \to \bar{\nu}_\mu + \mu^-$

(iii) $p + \bar{p} \to p + \bar{p}$

(iv) $e^- + p \to \nu_e + n$

[7 marks]

1.5 Draw *one* Feynman diagram for each of the interactions of question 1.4.

[7 marks]

1.6 By considering changes in appropriate quantum numbers, determine *all* the conservation laws which are violated in each of the following interactions.

(i) $p + \bar{n} \to n + \bar{p}$

(ii) $\nu_\mu + n \to p + e^-$

(iii) $\Xi^- \to \pi^0 + e^- + \bar{\nu}_\mu$

[7 marks]

1.7 Describe the mechanisms by which a beam of fixed momentum negative muons can be produced in a proton accelerator.

[7 marks]

1.8 Why was it necessary to introduce the concept of *colour* into the quark model? Explain why baryons cannot be made of 2, 4 or 5 quarks.

[7 marks]

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SECTION B. Answer any **TWO** questions from this section.

2. 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) Present a qualitative argument that 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 $\sim 10^{16}$ GeV c^{-2} are needed. Draw a quark Feynman diagram showing how these gauge bosons could lead to proton decay.

[7 marks]

f) Discuss the experimental evidence for proton decay and the implications for GUTs.

[5 marks]

3. a) Define the operations of *parity*, *P*, and *charge conjugation*, *C*. Show that, if $\boldsymbol{P}|\psi\rangle = p|\psi_p\rangle$ and $\boldsymbol{C}|\psi\rangle = c|\psi_c\rangle$, then $p = \pm 1$ and $c = \pm 1$.

[4 marks]

b) Present an argument that charged pions have negative intrinsic parity but are not eigenstates of *C*.

[4 marks]

c) Present arguments that the quantum numbers associated with *C* and *P* are not conserved by the weak interaction, while those associated with the combined operation *CP* might be expected to be.

[7 marks]

d) Show that the strong interaction states K^0 and $\overline{K}^0$ are not eigenstates of *CP*. Construct linear combinations of these two states which are eigenstates of *CP* and determine their eigenvalues.

[5 marks]

e) Experiments with neutral kaons have shown that the weak interaction does *not* conserve *CP*. Explain this statement. Briefly describe a recent result, using different particles, which appears to confirm this observation. [You may assume that $\boldsymbol{CP}|\pi\pi\rangle = |\pi\pi\rangle$ and $\boldsymbol{CP}|\pi\pi\pi\rangle = -|\pi\pi\pi\rangle$.]

[6 marks]

f) Briefly discuss *time reversal symmetry*, *T*, and the evidence concerning the conservation of the quantum numbers associated with the combined operation *CPT*.

[4 marks]

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4. a) What is meant be the statement *the group SU(3) has eight generators*?

[2 marks]

b) From these generators, it is possible to form the step operators $I_\pm$, $U_\pm$ and $V_\pm$ which induce the following changes:

$$I_\pm \text{ causes } \Delta Y = 0, \Delta I_3 = \pm 1$$
$$U_\pm \text{ causes } \Delta Y = \pm 1, \Delta I_3 = \mp \tfrac{1}{2}$$
$$V_\pm \text{ causes } \Delta Y = \pm 1, \Delta I_3 = \pm \tfrac{1}{2}$$

where Y is the hypercharge and I_3 is the third component of isospin. Draw the fundamental triplet of SU(3) and use it to illustrate the actions of the step operators.

[6 marks]

c) Use the step operators to form the weight diagram of the SU(3) multiplet (4,3). From the rule governing the occupancy of the sites of a multiplet, determine the dimensionality of (4,3).

[10 marks]

d) By using an appropriate line of constant Y from the (4,3) weight diagram, or otherwise, show that $5 \otimes 4 = 8 \oplus 6 \oplus 4 \oplus 2$.

[6 marks]

e) Use the fundamental triplet and its conjugate to form the SU(3) multiplets representing mesons. Hence show that $(1,0) \otimes (0,1) = (1,1) \oplus (0,0)$.

[6 marks]

5 Write notes on *two* of the following:

a) The Dirac equation and its implications.

[15 marks]

b) The discovery of weak neutral currents and its significance for unified theories.

[15 marks]

c) Supersymmetry and any implications for the “missing matter” of the Universe.

[15 marks]