Queen Mary
University of London

BSc/MSci EXAMINATION

PHY-653 Elementary Particle Physics

Time Allowed: 2 hours 15 minutes

Date: 14 May 2007

Time: 14:30

Answer ALL questions in section A. Answer ONLY TWO questions from section B. Section A carries 40 marks, each question in section B carries 30 marks. An indicative marking-scheme is shown in square brackets [ ] after each part of a question.

COMPLETE ALL ROUGH WORKINGS IN THE ANSWER BOOK AND CROSS THROUGH ANY WORK WHICH IS NOT TO BE ASSESSED.

NUMERIC CALCULATORS ARE PERMITTED IN THIS EXAMINATION.

Data:

Speed of light	c	3.0×10^{8}	$\mathrm{m \cdot s^{-1}}$
Elementary charge	e	1.60×10^{-19}	C

YOU ARE NOT PERMITTED TO START READING THIS QUESTION PAPER UNTIL INSTRUCTED TO DO SO BY AN INVIGILATOR

Questions:

Section A :-

A1. A neutral kaon K^0 (mass $M_{K^0} = 494\text{MeV}/c^2$) with momentum $\mathbf{p}_{K^0}$ decays into two pions (mass $M_{\pi^\pm} = 140\text{MeV}/c^2$):

$$K^0 \rightarrow \pi^+ + \pi^-.$$

Why are the momenta $\mathbf{p}_\pm$ of the pions and that of the kaon coplanar? [2]
If $|\mathbf{p}_{K^0}| = 100$ MeV/c, and the pion momenta make equal angles with $\mathbf{p}_{K^0}$, what are the energies $E_\pm$ of the two pions? [4]
Neutral kaons can also decay into three pions:

$$K^0 \rightarrow \pi^+ + \pi^- + \pi^0.$$

The neutral pion escapes detection. How can this mode be distinguished experimentally from the two pion mode? [2]

A2. Particles of charge e and mass m in a collider move in a circular orbit of radius R. They each radiate an amount ΔE of energy through synchrotron radiation in every complete circuit, where

$$\Delta E = \frac{4\pi K e^2 \beta^2 \gamma^4}{3R},$$

with $\beta = v/c$ and $\gamma = (1-\beta^2)^{-1/2} = E/mc^2$ and $K \equiv \frac{1}{4\pi\epsilon_0} \approx 8.99 \times 10^9$ N·m^2/C^2. The LHC has a radius $R = 4.3$ km, and will collide 7 TeV protons (mass $M_p = 0.94\text{GeV}/c^2$) in its two counter-rotating beams. Each beam will contain approximately 2,800 bunches of protons, with 1.15×10^{11} protons per bunch. What is the expected total power loss from the two beams through synchrotron radiation? [8]

A3. Draw Feynman diagrams that illustrate the interactions of the quarks and leptons involved in the following processes:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu;$$

$$n \rightarrow p + e^- + \overline{\nu}_e;$$

$$\Delta^{++} \rightarrow p + \pi^+;$$

$$e^+ + e^- \rightarrow \mu^+ + \mu^-$$

Identify any bosons involved, and state whether the interactions are strong, electromagnetic or weak. [8]

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A4. A particle X was observed produced by the following strong interaction of a negative kaon with a proton:

$$K^- + p \to X + K^+ + K^0.$$

Draw a Feynman diagram that describes this, and so determine the quark content of the particle X. [6]
What was the particle X? [2]

A5. The Sudbury Neutrino Observatory (SNO) is designed to detect all types of neutrinos coming from the Sun. It consists of 1,000 tonnes of heavy water D_2O in an acrylic vessel viewed by 10,000 photomultiplier tubes. The neutrino interactions observed are of three types:

$$\nu_e + d \to p + p + e^- \quad \text{Charged Current (CC);}$$
$$\nu_X + d \to p + n + \nu_X \quad \text{NeutralCurrent (NC);}$$
$$\nu_X + e^- \to \nu_X + e^- \quad \text{Electron Scattering (ES).}$$

Draw the Feynman diagrams (one each for CC and NC, *two* for ES) that describe these interactions, identifying in each case the boson involved. [8]

Section B

B1.

(i) Explain how the observation of two long-lived particles in the reaction

$$\pi^- + p \to K^0 + \Lambda^0$$

led to the introduction of a new quantum number called 'strangeness'. [6]

(ii) Draw Feynman diagrams to illustrate the reaction and the subsequent decays, carefully labelling all the quarks and exchanged particles involved. [8]

(iii) Write down the quark content of the $K^0, \overline{K}^0, K^+$ and K^- and explain how the reactions

$$\overline{K}^0 + p \to \Lambda^0 + \pi^+ \quad \text{and} \quad K^0 + p \to \Lambda^0 + K^0 + K^+$$

can be used to show that the K^0 and $\overline{K}^0$ are distinct particles with respect to the strong interaction. [8]

(iv) Explain why K^0 and $\overline{K}^0$ are not eigenstates of the CP operator. Write down the two states K_1 and K_2 which are eigenstates of CP and show that they have CP eigenvalues +1 and -1 respectively. [8]

[The masses of K^0, K^+ and Λ^0 are 0.498 GeV/c^2, 0.494 GeV/c^2 and 1.116 GeV/c^2 respectively.]

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B2. (i) Explain the difference between **leptonic, semi-leptonic** and **non-leptonic** weak interactions or decays. [8]

(ii) Draw a Feynman diagram to illustrate a **semi-leptonic decay** involving a change in strangeness, $\Delta S = 1$. [4]

(iii) Describe briefly how Cabibbo theory explains the factor of 20 difference in lifetime between $\Delta S = 0$ and $\Delta S = 1$ decays. [6]

(iv) Given the following approximate values for the magnitudes of the CKM matrix elements, calculate the branching ratios of a **real** W into all possible quark-antiquark and lepton-antilepton pairs, taking account of colour, but ignoring phase space effects.

$$\begin{pmatrix} 0.97 & 0.22 & 0.004 \\ 0.22 & 0.97 & 0.04 \\ 0.004 & 0.04 & 0.99 \end{pmatrix}$$

[8]

(v) Hence show that the branching ratio of $W \to$ hadrons is approximately 67%. [4]

B3. (i) Describe the main properties of **neutrinos**. [4]

(ii) Explain why two ν_μ are produced for each ν_e from the decay of pions from cosmic ray interactions in the upper atmosphere. [5]

(iii) The fact that this ratio is measured to be 1.36 is known as the **atmospheric neutrino problem**. Explain briefly what is meant by the **solar neutrino problem**. [5]

(iv) Explain how both of these problems can be resolved by **neutrino oscillations**. [8]

(v) What experiments are designed to study neutrino oscillations, and what is it hoped to measure? [8]

End of Examination Paper
Professor John M Charap