



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         $c$   $3.0 \times 10^8$          $\text{m} \cdot \text{s}^{-1}$   
                                 Elementary charge     $e$   $1.60 \times 10^{-19}$     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  $|\mathbf{p}_{K^0}| = 100 \text{ MeV}/c$ , 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  $\Delta E$  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  $K \equiv \frac{1}{4\pi\epsilon_0} \approx 8.99 \times 10^9 \text{ N}\cdot\text{m}^2/\text{C}^2$ . The LHC has a radius  $R = 4.3 \text{ km}$ , 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  $1.15 \times 10^{11}$  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:

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

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

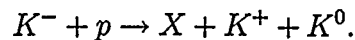
$$\Delta^{++} \rightarrow p + \pi^+;$$

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

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

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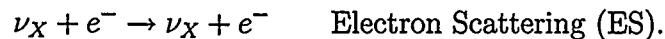
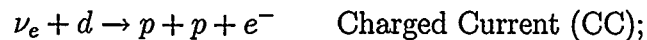
A4. A particle  $X$  was observed produced by the following strong interaction of a negative kaon with a proton:



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:

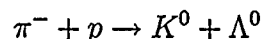


Draw the Feynman diagrams (one each for CC and NC, *two* for ES) that describe these interactions, identifying in each case the boson involved. [8]

## Section B

B1.

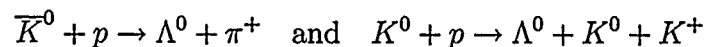
(i) Explain how the observation of two long-lived particles in the reaction



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  $K^0$ ,  $\bar{K}^0$ ,  $K^+$  and  $K^-$  and explain how the reactions



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

(iv) Explain why  $K^0$  and  $\bar{K}^0$  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  $\Lambda^0$  are  $0.498 \text{ GeV}/c^2$ ,  $0.494 \text{ GeV}/c^2$  and  $1.116 \text{ GeV}/c^2$  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  $W \rightarrow$  hadrons is approximately 67%. [4]

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

(ii) Explain why two  $\nu_\mu$  are produced for each  $\nu_e$  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