NATURAL SCIENCES TRIPOS Part III

Tuesday 18 January 2005 2.00 to 3.30

EXPERIMENTAL AND THEORETICAL PHYSICS (4)
Particle Physics

Answer **two** *questions only. The approximate number of marks allotted to each part of a question is indicated in the right hand margin where appropriate. The paper contains FOUR sides (including this one) and is accompanied by a book giving values of constants and containing mathematical formulae which you may quote without proof.*

STATIONERY REQUIREMENTS
20 Page Answer Book
Rough Work Pad
Metric Graph Paper

SPECIAL REQUIREMENTS
Mathematical Formulae Handbook

You may not start to read the questions printed on the subsequent pages of this question paper until instructed that you may do so by the Invigilator.

1 Write down the possible final states consisting of a charged kaon, a neutral kaon and a charged pion which can be produced in antiproton-proton collisions via the strong interactions, giving reasons for your answer. Explain why these final states are useful for the study of CP violation. [4]

$\left[\mathrm{K}^+ = (\mathrm{u\bar{s}}),\ \mathrm{K}^0 = (\mathrm{\bar{s}d}),\ \pi^+ = (\mathrm{u\bar{d}})\right]$

Show that the $\pi^+\pi^-$ final state produced in the decay of a neutral kaon is an eigenstate of CP with eigenvalue +1. [4]

[*Kaons and pions are spin zero particles.*]

The strangeness eigenstates K^0 and $\overline{\mathrm{K}}^0$ are related to the mass eigenstates $\mathrm{K_S}$ and $\mathrm{K_L}$ and to the CP eigenstates K_1^0 ($CP = +1$) and K_2^0 ($CP = -1$) as

$$\mathrm{K}^0 \propto \mathrm{K_L} + \mathrm{K_S}, \qquad \overline{\mathrm{K}}^0 \propto \mathrm{K_L} - \mathrm{K_S},$$
$$\mathrm{K_S} \propto \mathrm{K}_1^0 + \epsilon \mathrm{K}_2^0, \qquad \mathrm{K_L} \propto \mathrm{K}_2^0 + \epsilon \mathrm{K}_1^0,$$

where $\epsilon = |\epsilon| e^{i\phi}$ is a complex constant. For a neutral kaon which is initially produced as a K^0, show that the decay rate to $\pi^+\pi^-$ at a proper time $t > 0$ is given by

$$\Gamma(\mathrm{K}^0_{t=0} \to \pi^+\pi^-) \propto e^{-\Gamma_\mathrm{S} t} + |\epsilon|^2 e^{-\Gamma_\mathrm{L} t} + 2|\epsilon| e^{-(\Gamma_\mathrm{S}+\Gamma_\mathrm{L})t/2} \cos(\Delta m\, t - \phi)$$

where $\Gamma_\mathrm{S} = 1/\tau_\mathrm{S}$, $\Gamma_\mathrm{L} = 1/\tau_\mathrm{L}$, τ_S and τ_L are the $\mathrm{K_S}$ and $\mathrm{K_L}$ lifetimes, and $\Delta m \equiv m_\mathrm{L} - m_\mathrm{S}$ is the difference in the $\mathrm{K_L}$ and $\mathrm{K_S}$ masses. What is the corresponding expression for the decay rate $\Gamma(\overline{\mathrm{K}}^0_{t=0} \to \pi^+\pi^-)$ for an initial $\overline{\mathrm{K}}^0$? [8]

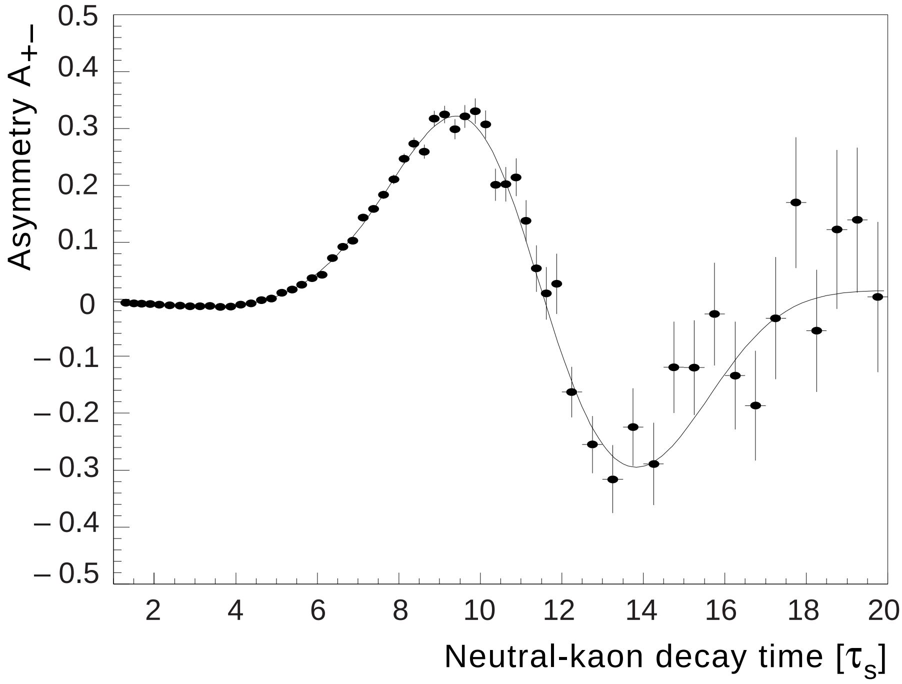
The asymmetry A_{+-} in the K^0 and $\overline{\mathrm{K}}^0$ decay rates to $\pi^+\pi^-$ is given by

$$A_{+-} \equiv \frac{\Gamma(\overline{\mathrm{K}}^0_{t=0} \to \pi^+\pi^-) - \Gamma(\mathrm{K}^0_{t=0} \to \pi^+\pi^-)}{\Gamma(\overline{\mathrm{K}}^0_{t=0} \to \pi^+\pi^-) + \Gamma(\mathrm{K}^0_{t=0} \to \pi^+\pi^-)} \approx \frac{-2|\epsilon| e^{\Gamma_\mathrm{S} t/2} \cos(\Delta m\, t - \phi)}{1 + |\epsilon|^2 e^{\Gamma_\mathrm{S} t}},$$

where the last expression on the right-hand side (which need not be derived) uses the approximation $\Gamma_\mathrm{L} \ll \Gamma_\mathrm{S}$. The figure overleaf shows measurements from the CPLEAR experiment of the asymmetry A_{+-} as a function of t/τ_S. By considering the times where the asymmetry reaches a maximum and next passes through zero, or otherwise, obtain *estimates* of the quantities $|\epsilon|$ and ϕ. [8]

$\left[\Delta m = 3.5 \times 10^{-12}\,\mathrm{MeV},\ \tau_\mathrm{S} = 0.9 \times 10^{-10}\,\mathrm{s},\ \hbar = 6.58 \times 10^{-22}\,\mathrm{MeV\,s}\right]$

Explain briefly how CP violation is accommodated within the Standard Model and outline the current experimental constraints on parameters relevant to CP violation derived from measurements using kaons or B hadrons. [6]


Asymmetry A_{+-}
0.5
0.4
0.3
0.2
0.1
0
– 0.1
– 0.2
– 0.3
– 0.4
– 0.5
2
4
6
8
10
12
14
16
18
20
Neutral-kaon decay time [τ_s]

(TURN OVER

2 Write brief accounts of **two** of the following:

(a) proton and neutron elastic form factors and their measurement; [15]

(b) colour SU(3) and colour potentials; [15]

(c) deep-inelastic (anti)neutrino-nucleon scattering; [15]

(d) experimental evidence for neutrino oscillations. [15]

3 State what is meant by the terms *helicity* and *chirality* and explain how they are related for highly relativistic particles and antiparticles. [5]

The vertex factor for the interaction between a Z^0 boson and a fermion f is proportional to $c_{\mathrm{L}}^{\mathrm{f}}\gamma^{\mu}(1-\gamma^5)+c_{\mathrm{R}}^{\mathrm{f}}\gamma^{\mu}(1+\gamma^5)$. Without detailed mathematics, explain why this restricts the possible spin states of the incoming and outgoing particles and antiparticles in $\mathrm{e^+e^-} \to \mathrm{Z}^0 \to \mathrm{f\bar{f}}$ scattering in the relativistic limit. Draw diagrams illustrating the allowed spin configurations for this process in the centre of mass frame. For the case where the electron is right-handed and the fermion is left-handed, explain (still without detailed mathematics) why the differential cross section in the centre of mass frame takes the form

$$\frac{\mathrm{d}\sigma_{\mathrm{RL}}}{\mathrm{d}\Omega} \propto (c_{\mathrm{R}}^{\mathrm{e}})^2(c_{\mathrm{L}}^{\mathrm{f}})^2(1-\cos\theta)^2$$

where θ is the angle between the electron and fermion directions. Write down similar expressions for the other allowed spin configurations. [9]

Find the *relative* total cross sections σ_{R} and σ_{L} for the production of a right-handed or left-handed fermion in collisions of unpolarised electrons with unpolarised positrons on the peak of the Z^0 resonance. Hence show that the average helicity (average polarisation) of the final state fermion in such collisions is

$$P_{\mathrm{f}} = \frac{(c_{\mathrm{R}}^{\mathrm{f}})^2-(c_{\mathrm{L}}^{\mathrm{f}})^2}{(c_{\mathrm{R}}^{\mathrm{f}})^2+(c_{\mathrm{L}}^{\mathrm{f}})^2}\ .$$

The average polarisation of the τ^- lepton in $\mathrm{e^+e^-} \to \tau^+\tau^-$ scattering has been measured by experiments at the LEP Collider to be $P_\tau = -0.1465$. Find the value of $\sin^2\theta_{\mathrm{W}}$ corresponding to this measurement. [9]

$\left[c_{\mathrm{R}}^{\mathrm{f}} = -Q_{\mathrm{f}}\sin^2\theta_{\mathrm{W}},\ c_{\mathrm{L}}^{\mathrm{f}} = I_W^3 - Q_{\mathrm{f}}\sin^2\theta_{\mathrm{W}}\right]$

Outline how the electroweak sector of the Standard Model can be accurately tested using experimental measurements made on the Z^0 resonance. Explain why such measurements provide indirect information on the W boson, top quark and Higgs boson masses, and summarise the current status of direct and indirect measurements of these masses. (Precise numerical values are not expected.) [7]

END OF PAPER