Speed of light c	$= 2.998\times10^{8}\ \mathrm{m\,s^{-1}}$
Reduced Planck constant h	$= 1.055\times10^{-34}\ \mathrm{J\,s} = 197\ \mathrm{MeV\,fm}$
Rest mass of proton m_{p}	$= 1.673\times10^{-27}\ \mathrm{kg} = 938.3\ \mathrm{MeV\,c^{-2}}$
Rest mass of π^{-} m_{π}	$= 139.6\ \mathrm{MeV\,c^{-2}}$
Rest mass of K^{-} m_{K}	$= 493.7\ \mathrm{MeV\,c^{-2}}$
Rest mass of Λ m_{Λ}	$= 1115.7\ \mathrm{MeV\,c^{-2}}$
Rest mass of Σ^{0} m_{Λ}	$= 1192.6\ \mathrm{MeV\,c^{-2}}$
Rest mass of Ξ^{0} m_{Ξ}	$= 1314.9\ \mathrm{MeV\,c^{-2}}$
Rest mass of W boson m_{W}	$\approx 80\ \mathrm{GeV\,c^{-2}}$

SECTION A – Answer SIX parts of this section

1.1) Write down the differences between *fermions* and *bosons*. State whether the following particles are fermions or bosons: neutrino, kaon, photon, proton, gluon.

[7 marks]

1.2) A particle X decays at rest into a Λ and a K^{-}. Each of the decay products has a momentum of $211\ \mathrm{MeV\,c^{-1}}$. Calculate the mass of X. An alternative decay mode is $\mathrm{X}\rightarrow\Xi^{0}+\pi^{-}$; calculate the momenta of the decay products in this case, assuming that the decay takes place at rest.

[7 marks]

1.3) By considering the relevant conservation laws determine which of the following reactions and decays are allowed by first-order processes.

(i) $\mathrm{S}^{0}\rightarrow ? + ?$

(ii) $? \rightarrow \mathrm{S}^{0} + ?$

(iii) $\mathrm{K}^{+}+\mathrm{n}\rightarrow\Lambda+\mathrm{p}^{+}$

(iv) $\mathrm{K}^{-}+\mathrm{n}\rightarrow\Lambda+\mathrm{p}^{-}$

For those which are allowed, state which force is most likely to be involved. For those which are not allowed, state a conservation law which is violated.

[7 marks]

1.4) State all forces (other than gravity) which could mediate each of the following processes. In the case of weak interactions indicate whether charged or neutral current processes, or both, might be responsible.

(i) $e^{+}+e^{-}\rightarrow e^{+}+e^{-}$

(ii) $e^{+}+e^{-}\rightarrow\mu^{+}+\mu^{-}$

(iii) $?_{e}+e^{-}\rightarrow ?_{e}+e^{-}$.

Draw *one* appropriate Feynman diagram in each case. The diagrams for (i) and (ii) should be topologically different to each other.

[7 marks]

1.5) 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]

1.6) 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]

1.7) Briefly describe the processes by which electromagnetic and hadron calorimeters measure the energies of particles. Explain why electromagnetic calorimeters are more accurate than hadron calorimeters.

[7 marks]

1.8) The strong interaction is considered to take place through the exchange of gluons between quarks. Which discrete quantum number is exchanged? Describe qualitatively an important difference, resulting from the quantum number referred to, between the exchange of photons in the electromagnetic interaction and gluon exchange.

[7 marks]

SECTION B – Answer TWO questions

2) a) Discuss the reasons for the introduction of the concept of *weak neutral currents.* Draw a Feynman diagram, in terms of neutrinos and quarks, for the neutral current process

$$?_\mu + p \rightarrow ?_\mu + p$$

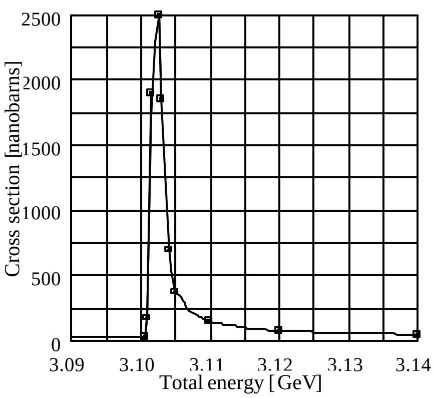
[8 marks]

b) Draw Feynman diagrams for a neutral current process and for a charged current process which could each describe the decay

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

Discuss how the low observed rate of this decay led to the prediction of the charmed quark and an estimate of its mass m_C.

[14 marks]



c) The figure shows a plot of the cross section for $e^+ + e^- \rightarrow e^+ + e^-$ as a function of total energy. Discuss why this result is considered to be due to the production and subsequent decay of a meson consisting of a charmed quark and a charmed antiquark. From the plot *estimate* the mass of this meson, and discuss whether it is consistent with the predicted value of m_C. Also obtain an estimate of the lifetime and state why this estimate is certainly inaccurate.

[8 marks]

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

[2 marks]

b) State why the quark structures of some baryons were incompatible with the quark model in its original form. How was this problem 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]

d) Five hadrons have the quantum numbers given in table 3.1.

Table 3.1. Quantum numbers of observed hadrons.

Hadron	Electric charge, *Q*	Baryon no., *B*	Strangeness, *S*	Charm, *C*	Bottom, *B̲*	Top, *T*
(i)	–1	+1	–2	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	+1	0	+1	0

Determine the quark constituents of each of these hadrons, and those of any partner particles differing only in electric charge.

[13 marks]

e) Hadrons with the quantum numbers given in table 3.2 have not yet been observed.

Table 3.2. Possible quantum numbers of hadrons that have not been observed.

Hadron	Electric charge, *Q*	Baryon no., *B*	Strangeness, *S*	Charm, *C*	Bottom, *B̲*	Top, *T*
(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

Determine which of these states are compatible with the quark model and which are not.

[5 marks]

For parts (d) and (e) of question 3 you may find the table 3.3 helpful.

Table 3.3. Quantum numbers of the quarks.

Quark	Electric charge, *Q*	Baryon no., *B*	Strangeness, *S*	Charm, *C*	Bottom, *B̲*	Top, *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

SEE NEXT PAGE

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

[3 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:

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

State the meaning of Y and I_3. Draw the fundamental triplet of SU(3) and use it to illustrate the actions of the step operators. Describe how the boundary of the multiplet (p,q) is formed.

[8 marks]

c) Use the step operators and the rule governing the occupancy of the sites to form the weight diagram of the SU(3) multiplet (4,1). State what distinguishes states occupying the same sites, and determine the dimensionality of (4,1).

[7 marks]

d) By using appropriate lines of constant Y from the (4,1) weight diagram, or otherwise, show that $4 \otimes 2 = 5 \oplus 3$ and $5 \otimes 2 = 6 \oplus 4$.

[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) a) State three properties of neutrinos according to the Standard Model.

[3 marks]

b) Recently several teams working on experiments with neutrinos have reported new results. These include: (i) the study using the Super-Kamiokande detector of neutrinos produced in the upper atmosphere of the Earth via cosmic ray interactions; (ii) the observation of solar neutrinos at the Sudbury Neutrino Observatory; and (iii) the measurement of the weak mixing angle by the NuTeV collaboration. Make brief notes on each of the experiments, emphasising those aspects which allowed the new results to be obtained.

[18 marks]

c) Discuss the relative significance of each of the results and select the one which you believe to be the most significant, giving reasons for your choice.

[9 marks]

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