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 neutron m_n = $939.6\,\mathrm{MeV\,c^{-2}}$
Rest mass of muon m_μ = $105.7\,\mathrm{MeV\,c^{-2}}$
Rest mass of charged kaon m_K = $493.7\,\mathrm{MeV\,c^{-2}}$

SECTION A – Answer SIX parts of this section

1.1) By considering the relevant conservation laws determine which of the following reactions and decays are allowed by first-order processes. You should assume that all the particles involved are unbound.

(i) $p^0 \rightarrow ? + ?$

(ii) $p \rightarrow n + e^+ + ?_e$

(iii) $\mu^+ \rightarrow e^+ + e^+ + e^-$

(iv) $K^+ + n \rightarrow \Sigma^+ + p^0$

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

[7 marks]

1.2) A charged kaon decays at rest into a muon and a neutrino (e.g., $K^+ \rightarrow ?\mu^+ + \nu_\mu$). The energy of the muon is measured to be at least 258.1 MeV. Show that the rest mass of the neutrino is $m_\nu < 8.0\,\mathrm{MeV\,c^{-2}}$.

[7 marks]

1.3) Explain, using suitably labelled Feynman diagrams, why the neutrino scattering processes $?_e + e^- \rightarrow ?_e + e^-$ and $?_\mu + e^- \rightarrow ?_\mu + e^-$ proceed at different rates.

[7 marks]

1.4) Describe qualitatively how Gell-Mann predicted the charge, strangeness and mass of the Ω^-.

[7 marks]

1.5) Define the system of natural units. Hence obtain values, in SI units, for the natural units of length, energy and time. What is the muon mass in natural units?

[7 marks]

1.6) Briefly describe the mechanisms by which beams of muon neutrinos can be produced in a proton accelerator. Why is it not possible to obtain an accelerator neutrino beam containing just one type of neutrino or antineutrino?

[7 marks]

1.7) Interactions such as $e^+ + e^- \rightarrow e^+ + \mu^-$ may be observed in electron–positron colliding beam experiments when the energy in each beam is above about 1.8 GeV. Given that the measured energy in the final state is lower than that in the initial state, discuss the interpretation of such observations. Write down a full set of reactions describing the processes which are taking place.

[7 marks]

1.8) What is meant by the *three generations of matter*? State one piece of evidence which indicates that there is not a fourth generation.

[7 marks]

SECTION B – Answer TWO questions

2) a) What are the advantages and disadvantages of colliding beam machines compared to accelerators used for fixed target experiments?

[6 marks]

b) Briefly describe the properties which an ideal detector for use with a colliding beam experiment should have. State how these ideals may be approached in practice.

[8 marks]

c) A negative kaon of momentum 12.2790 GeV interacts with a proton, which you may assume to be free and stationary. The interaction produces a positive particle A^+, a negative particle B^- and an undetected third particle X, i.e., the interaction observed is

$$K^- + p \rightarrow A^+ + B^- + X\,.$$

Some experimentally measured quantities are shown in the table below. Complete the table, and identify the particles A^+, B^- and X.

You should note that, due to experimental error, the masses that you calculate may not correspond precisely with tabulated values, but should be close to them.

Particle	Momentum [GeV]	Energy[a] [GeV]	Angle[b]	Mass [MeV]	Strangeness *S*
K^-	12.2790		0	493.7	–1
p	0		0	938.3	0
A^+	7.6129	7.6292	+9.0°		
B^-	2.5154	2.5193	+5.5°		
X					

[a]This is the total relativistic energy
[b]The angle is defined as positive to the right and negative to the left of the original K^- direction.

[16 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 (assuming a neutrino rest mass of zero), 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. [You may assume that $\boldsymbol{CP}|\pi\pi\rangle = |\pi\pi\rangle$ and $\boldsymbol{CP}|\pi\pi\pi\rangle = -|\pi\pi\pi\rangle$.]

[5 marks]

f) Briefly and qualitatively discuss *strangeness oscillations* and *regeneration* (a detailed analysis is not required).

[5 marks]

4) a) Why was it necessary to introduce the concept of *colour* into the quark model? What is meant by the statement "only *white* or *colourless* particles are directly observable"?

[6 marks]

b) The strong force is now considered to be due to the exchange of gluons carrying colour between two quarks. Explain how this is related to the strong *nuclear* force between, for example, two nucleons. Explain how colour leads to the confinement of quarks inside hadrons.

[5 marks]

c) Draw a quark Feynman diagram illustrating the first-order strong interaction between a red quark and a blue quark, explicitly labelling all particles involved with their colour quantum numbers.

[5 marks]

d) By considering colour to form a fundamental triplet of SU(3), or otherwise, show that there are eight independent gluons which contribute to the strong interaction. There is also one which does not contribute; explain why.

[11 marks]

e) Briefly discuss one piece of experimental evidence for the existence of gluons.

[3 marks]

5) a) Briefly discuss each of the following, in each case giving brief experimental details and indicating whether the result has actually been obtained.

(i) The production of cold anti-hydrogen atoms and the measurement of their properties.

(ii) The observation of the rate of neutral current interactions of solar neutrinos.

(iii) The measurement of the Higgs boson mass.

[7 marks each]

b) Discuss the relative significance of each of the results and select that which you believe to be *currently* the most significant, giving a reason for your choice. What new knowledge at a fundamental level could each of them ultimately produce?

[9 marks]