Mark scheme for Option J

1 **a** A fermion is a particle with a half integral spin; a boson has integral spin. **[1]**

b A meson consists of a quark and an antiquark,

whereas a baryon has three quarks. **[2]**

c **i** $Q = 3\times(-\frac{2e}{3}) = -2e$

$S = 0$ **[2]**

ii Two identical fermions cannot occupy the same quantum state. **[1]**

iii The Pauli principle applies to this particle.

Because the three otherwise identical quarks are distinguished by their different colour quantum numbers. **[2]**

2 **a** They have the same mass. **[1]**

b $Q = -Q$

Hence $Q = 0$. **[2]**

c It cannot be,

because the neutron and the antineutron are distinguished by their different baryon quantum numbers. **[2]**

3 **a** An interaction between two charged particles involves the exchange of energy and momentum between the particles.

In the case of the electromagnetic interaction, the exchanged energy and momentum are carried by the photon, which is emitted by one particle and received by the other.

The whole process lasts for a sufficiently small amount of time so that any violations of energy conservation do not become observable. **[3]**

b The range is inversely proportional to mass,

and so is infinite for the electromagnetic interaction. **[2]**

c **i** $W^{\pm}$
Z^0 **[2]**

ii

$$R = \frac{6.6\times10^{-34}}{4\pi\times(\frac{100\times10^{9}}{(3\times10^{8})^{2}}\times1.6\times10^{-19})\times3\times10^{8}}$$ **[2]**

$$= 9.8\times10^{-19} \approx 10^{-18}\text{ m.}$$

Exam tip: notice the conversion of mass from GeV c^{-2} to kg.

d **i**

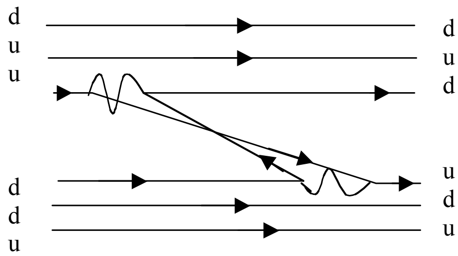
$$R = \frac{6.6\times10^{-34}}{4\pi(\frac{140\times10^{6}}{(3\times10^{8})^{2}}\times1.6\times10^{-19})3\times10^{8}};$$ **[2]**

$$\approx 10^{-15}\text{ m}$$

ii Protons and neutrons are described in terms of quarks.

One gluon exchange in incoming proton/neutron.

One gluon exchange in outgoing proton/neutron.



[3]

4 **a** **i** It is virtual (because it cannot be observed due to colour confinement and so must join another particle after a very short time). **[1]**

ii Up (gluons do not change flavour). **[1]**

iii Green and antiblue. **[2]**

b **i** Because if it did the baryon would have colour,

and in QCD colour is confined.

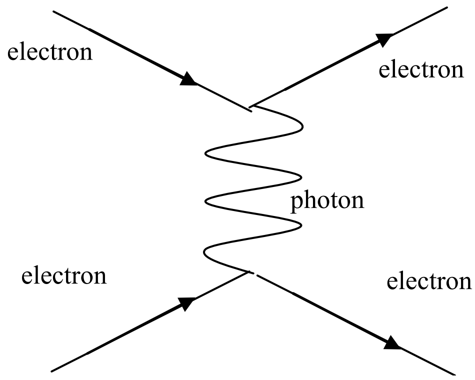
OR

It would violate the Pauli principle,

because the three quarks would be identical. **[2]**

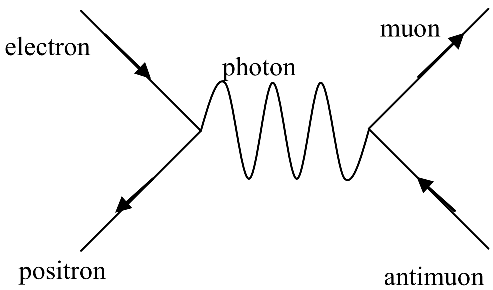
ii No, because it would violate colour confinement. **[1]**

5 **a** **i**



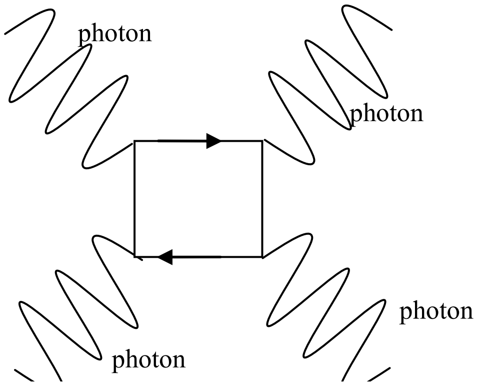
[1]

ii



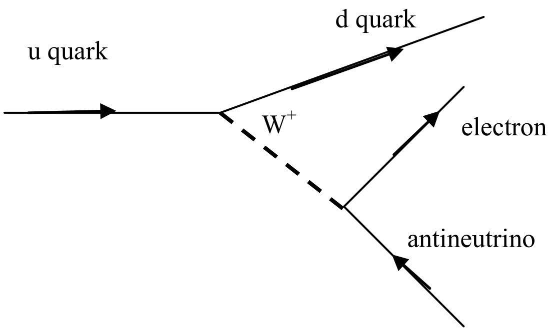
[1]

iii


photon
photon
photon
photon

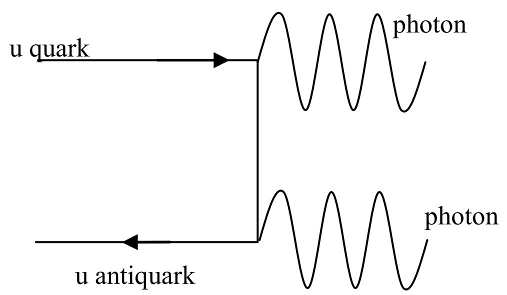
[1]

iv

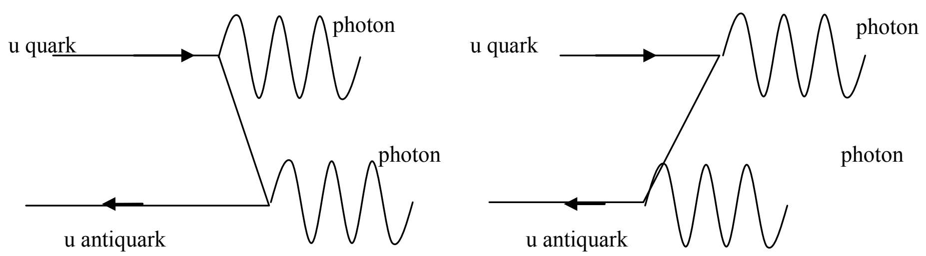

d quark
u quark
W+
electron
antineutrino

[1]

v



Exam tip: it is ok to draw the 'vertical' line above, but draw it slanted if you prefer. The following diagrams are equivalent to the one above.



[1]

6 **a** To resolve an object of size *d*, the wavelength used must be of the same order of magnitude as *d*.

So, in this case, it is of order 10^{-15} m. **[2]**

b The quarks are much smaller than a nucleus,

and so a much smaller de Broglie wavelength is required. **[2]**

7 **a** A liquid kept just below its boiling point has its pressure reduced so it begins to boil.

Bubbles from the boiling liquid will first form along the path of any charged particles that are moving through the liquid at that precise time.

A magnetic field bends the path of the particle into a circular path whose radius can be measured if a photograph of the path is taken. **[3]**

b The path of the particle is photographed and the radius R of the circular path in the magnetic field is measured.

From $R = \dfrac{mv}{qB}$ the momentum mv may be determined if first a reasonable estimate of the charge is made. **[2]**

c The data taken by the proportional wire chamber are digitized,

and therefore can be analysed much faster by a computer (as opposed to by a person in the case of bubble chamber photographs).

OR

In the case of the bubble chamber there is a 'dead time' in between photographs (there is no such thing in the case of the proportional chamber),

so there is continuous collection of data in the case of the proportional chamber. **[2]**

8 **a** Charged particles are inserted in a region of constant magnetic field and follow a circular path in split electrodes called the 'Dees'.

An alternating potential difference is established between the two 'D's whose frequency is the same as the frequency of revolution of the particles.

The particles are accelerated every time they cross the gap between the two 'D's. **[3]**

Exam tip: you may want to draw a diagram to help you with your answer here. **[3]**

b Determination of speed in terms of radius: $qvB = \dfrac{mv^2}{R} \Rightarrow v = \dfrac{qBR}{m}$.

$$E_{\max} = \frac{1}{2}mv^2 = \frac{1}{2}m\left(\frac{qBR}{m}\right)^2 = \frac{q^2B^2R^2}{2m}$$

$$E_{\max} = \frac{(1.6\times10^{-19})^2\times1.5^2\times2.0^2}{2\times1.67\times10^{-27}} = 6.89\times10^{-11}\ \text{J} = 431 \approx 430\ \text{MeV}.$$ **[3]**

c **i** A meson (because of baryon number conservation). **[1]**

ii Zero (by electric charge conservation). **[1]**

iii
$$E_A{}^2 = 2\times(140)^2\times(430+938)+938^2+140^2$$
$$E_A = 7384 \Rightarrow M_X c^2 = 7384-940 = 6444\ \text{MeV} \Rightarrow M_X \approx 6.4\ \text{GeV c}^{-2}.$$ **[2]**

9 **a** Charged particles travelling in circular paths enter cavities to which an alternating voltage is applied.

The voltage is synchronized with the particles so that they always ‘see’ an accelerating (and not a decelerating) voltage each time they enter the cavity. **[2]**

b The radius of the path of a charged particle in a magnetic field is $qvB = \frac{mv^2}{R} \Rightarrow R = \frac{mv}{qB}$.

Exam tip: you must make some reference to the radius and its dependence on the magnetic field.

As the particle accelerates, v increases but the radius has to stay constant.

Hence B must be variable (it must increase.) **[2]**

c The energy in a collision is 14 TeV:

$$\frac{3}{2}kT \approx 14\ \text{TeV}$$

$$T = \frac{2\times 14\times 10^{12}\times 1.6\times 10^{-19}}{3\times 1.38\times 10^{-23}} = 1.1\times 10^{17} \approx 10^{17}\ \text{K}.$$ **[3]**

10 **a** Experiments in which hadrons

receive large amounts of energy and momentum from bombarding particles (leptons). **[2]**

b **i** Deep inelastic scattering experiments measure the probability that a particular constituent will carry a certain fraction x of a baryon’s momentum (the ‘structure function’).

Experiments show a value of about $x = \frac{1}{3}$, indicating the presence of 3 charged constituents in baryons. **[2]**

Exam tip: the syllabus states to ‘analyse results of deep inelastic scattering experiments’, so some detail is expected here.

ii Experiments measure the total momentum of the hadron and the total momentum of the charged constituents.

The two are not the same, indicating the presence of neutral constituents (the gluons). **[2]**

Exam tip: the syllabus states to ‘analyse results of deep inelastic scattering experiments’, so some detail is expected here.

iii Asymptotic freedom is the decrease of the interaction strength as the energy transferred in the interaction increases.

The scattering pattern from hadrons is consistent with particles that very loosely interact with each other. **[2]**

11 **a** The energy required is $2m_e c^2$ and so $\frac{3}{2}kT \approx 2m_e c^2 \Rightarrow T = \frac{4m_2 c^2}{3k}$

$$T = \frac{4 \times 9.1 \times 10^{-31} \times (3 \times 10^8)^2}{3 \times 1.38 \times 10^{-23}} = 7.9 \times 10^9 \approx 10^{10} \text{ K.}$$ **[2]**

b There is no limit (electrons and positrons annihilate each other at any temperature). **[1]**

c In the early hot universe electrons and positrons annihilated each other but also high energy photons created electron–positron pairs out of the vacuum.

As the universe cooled down (to below the answer to **a**), the process of annihilation continued but not the process of pair creation, leaving the matter that we see today,

because in the early universe there was a slight amount of extra mass over antimatter. **[3]**

Exam tip: notice the detail required.

12 **a** **[2]** max from

The fundamental building blocks of matter in string theories are tiny one-dimensional strings as opposed to zero-dimensional point particles.

String theories are formulated in more than the 4 dimensions of particle physics.

String theories can in principle provide a quantum theory of gravity; theories based on particles have failed to do that. **[2]**

b The extra dimensions are curled up into compact manifolds,

and so are essentially unobservable at ordinary energies. **[2]**

