Chapter J3

Q1 (a) The neutron is $d\,d\,u$ and so the antineutron must be $\bar{d}\,\bar{d}\,\bar{u}$. The electric charge is $\left(+\dfrac{1}{3}+\dfrac{1}{2}-\dfrac{2}{3}\right)e=0$. The proton is $u\,u\,d$ and so the antiproton is $\bar{u}\,\bar{u}\,\bar{d}$ with electric charge $\left(-\dfrac{2}{3}-\dfrac{2}{3}+\dfrac{1}{3}\right)e=-e$, as expected.

Q2 (a) A hadron is any particle composed of quarks and/or antiquarks. (b) A meson is a particle composed of one quark and one antiquark. (c) A baryon is a particle composed of three quarks or three antiquarks.

Q3 The antiparticle of the K^{+} has quark structure $\bar{u}\,s$.

Q4 The photon.

Q5 It is -1 since this is an antibaryon.

Q6 (a) Violates: $-1\rightarrow 0+0$. (b) Conserves: $-1+1\rightarrow 0+0$. (c) Conserves: $-1+1\rightarrow 0+0+1-1$. (d) Violates: $+1\rightarrow 0+0$.

Q7 None, as a baryon in place of X would violate baryon number conservation.

Q8 Consider a decay such as $\Lambda^{0}\rightarrow p^{+}+\pi^{-}$ where the lambda baryon is uds. Notice that there is a strange quark on the left hand side of the decay but none on the right hand side. If this were a strong interaction process (or electromagnetic) the lifetime would be very short (less than about 10^{-20} s). However, the decay of the lambda has a much larger lifetime (of order 10^{-10} s). To explain this it was hypothesized that this long lifetime decay (and many others like it) were due to the weak interaction. The weak interaction being weaker than the strong would naturally lead to a long lifetime decay. To prevent this decay from happening via the strong or electromagnetic interactions, a new quantum number called strangeness was introduced that was assumed to be conserved in strong and electromagnetic interactions but not in weak interactions.

Q9 (a) The charge of $d\,\bar{s}$ is zero ($-\dfrac{1}{3}+\dfrac{1}{3}$). (b) The strangeness is $+1$.

Q10 (a) The charge of $c\,\bar{d}$ is e ($+\dfrac{2}{3}+\dfrac{1}{3}=1$). (b) The strangeness is zero since it does not have strange quarks in it.

Q11 To answer this question you must look up the quark content of the various particles in the textbook.

(a) Conserves: $0 + 0 \rightarrow +1 - 1$, (b) Conserves: $0 + 0 \rightarrow +1 - 1$, (c) Violates: $+1 \rightarrow 0 + 0$, (d) Violates: $0 + 0 \rightarrow 0 - 1$.

Q12 No. With just one strange quark the strangeness would be $-$ 1. The antiparticle would then have strangeness $+$ 1 and so could not be the same as the particle.

Q13 Since $\eta_c = c\,\bar{c}$ the antiparticle of the η_c is $\bar{c}\,c$ i.e. is the same as the η_c itself. However the antiparticle of the meson $K^0 = d\,\bar{s}$ would be $s\,\bar{d}$ and is different.

Q14 (a) $Q = +\dfrac{2}{3} - \dfrac{1}{3} - \dfrac{1}{3} = 0$, $S = 0 + 0 - 1 = -1$. (b) No. If they did the baryon itself would have color and this is not possible due to confinement.

Q15 (a) The spin of a quark is $s = \dfrac{\hbar}{2} = \dfrac{6.63 \times 10^{-34}}{4\pi} = 5.28 \times 10^{-35}$ J s . (b) The spins of the three quarks making up a baryon can be all up or two can be up and one down. In the first case the spin of the baryon is 3/2 and in the second it is 1/2. For mesons, both spins can be up leading to spin 1 or one up and one down leading to spin zero.

spin 3/2

baryons

spin 1/2

spin 1

mesons

spin 0
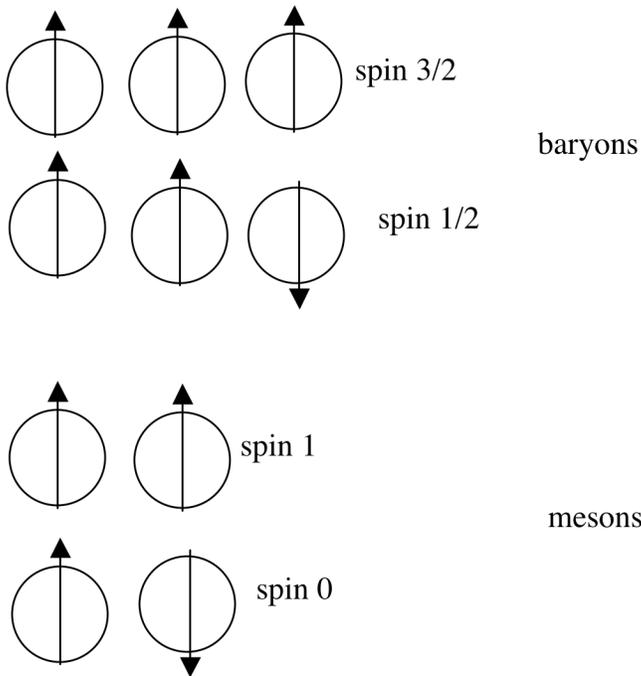
Q16 (a) The electron and the positron each have spin ½. If both spins are up, positronium has spin 1 (this state is called orthopositronium). If one spin is up and the other is down the total spin is zero (called parapositronium). (b) Parapositronium can decay into two photons whose spins are up and down making a spin of zero. Orthopositronium can decay into three photons where two photons have spin up and one has spin down making a total spin of 1. It cannot however decay into a single photon because this would violate

conservation of ordinary momentum – in a frame of reference in which the electron and positron have zero total momentum. Momentum must be conserved and so the end state must also have zero momentum. This cannot be achieved with a singe photon that has non – zero momentum.

Q17 (a) The quarks in the π^+ have opposite spins and the pion has zero spin. In the ρ^+, the spins are both up and the meson has spin 1. (b) The heavier meson will be the antiparticle of the ρ^+ and so will have the same mass as the ρ^+, i.e. $770\,\text{MeV c}^{-2}$.

Q18 There are spin 3/2 baryons consisting of identical quarks such as the combinations uuu or sss etc. In these baryons we have identical fermions occupying the same quantum state and this violates the Pauli principle. To save the principle color was introduced in order to distinguish the otherwise identical quarks in the same state.

Q19 (a) Confinement means that color cannot be observed. This implies that one cannot find isolated quarks or gluons. (b) The gluons will be very short lived and will produce hadrons along their path. The energy of the gluons will create quark antiquark pairs out of the vacuum and these will combine to make hadrons.

Q20 The quarks themselves do have color but in the combinations into which they bind in mesons and baryons the net color is zero. In mesons, this is because a quark with a definite color X binds with an antiquark with the anti – X color quantum number so the net color cancels out. In baryons a colorless combination can be achieved only if the three quarks each have different color.

Q21 (a) This is a weak interaction (beta decay) so the dashed line particle is a W boson. By charge conservation it must be W^-. (b) The weak interaction does not change the color so the color of the d and the u quarks is the same.

Q22 By color conservation the quark will be green. Gluons do not change the flavor of quarks so it will still be a c quark.

Q23 Meson X has strangeness +1 so it must have one anti strange quark. It also has one unit of positive charge and so it must be $u\bar{s}$. Meson Y has no strange quarks and negative charge so it must be $d\bar{u}$. Meson Z has no strange quarks and one unit of positive charge so it must be $u\bar{d}$. Meson W has one strange quark and since it has negative charge it must be $s\bar{u}$.

Q24 (a) See diagram in answers in textbook. (b) The momentum of the pion is zero and so the photons must have equal and opposite momenta in order to conserve momentum. This means that the photons have equal wavelengths. (c) The energy available to produce the two photons is 135 MeV so each photon must have an energy of 67.5 MeV. The photon wavelength is given by $\lambda = \dfrac{hc}{E} = \dfrac{6.63\times10^{-34}\times3\times10^{8}}{67.5\times10^{6}\times1.6\times10^{-19}} = 1.8\times10^{-14}\,\text{m}$. (d) Let

p be the momentum of the pion and λ_f, λ_b the forward and backward photon wavelengths. Then by momentum conservation: $\dfrac{h}{\lambda_f} - \dfrac{h}{\lambda_b} = p$ and so $\dfrac{h}{\lambda_f} > \dfrac{h}{\lambda_b}$. Hence $\lambda_f < \lambda_b$.

Q25 A partial answer is given in the textbook: the exchanged gluons (see diagram J3.10 on page 752) each have spin 1 and so their state has an integral spin, i.e. it appears as a meson. Another way of looking at this is to consider other diagrams leading to a strong interaction between hadrons. One such diagram is
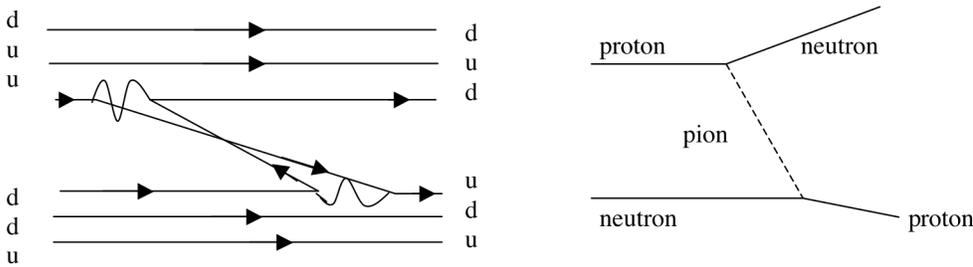
This shows proton – neutron scattering: $p + n \rightarrow p + n$. What appears to be exchanged in this case is a state consisting of a u quark and an anti d quark i.e. a meson again (a pion in this case).

Q26 We may deduce that $2m_u + m_d = 938$ and $m_u + 2m_d = 940$ (units of mass are MeV c^{-2}). We solve this system of equations to obtain the individual quark masses: from the first equation, $m_d = 938 - 2m_u$ and substituting this into the second gives

$$m_u + 2(938 - 2m_u) = 940$$
$$3m_u = 2 \times 938 - 940$$
$$m_u = 312 \,\text{MeV c}^{-2}$$

and so $m_d = 314 \,\text{MeV c}^{-2}$. (b) It follows that we can predict a mass of $312 + 314 = 626 \,\text{MeV c}^{-2}$ for the mass of the π^+ meson, which is clearly incorrect. (c) The reason for the disagreement is that both in the calculation of the masses in (a) as well as in the calculation of the mass of the pion in (b) we have neglected to take into account the sizable binding energy of the quarks. (There are also other technical reasons having to do with exactly what one means by the "mass" of the quarks.)

Q27 (Not for option D) (a) Electron neutrino. (b) Muon neutrino. (c) Tau antineutrino. (d) Electron antineutrino. (e) Electron antineutrino and tau neutrino.

Q28 (Not for option D) (a) No: $0 \rightarrow -1 + 0$. (b) No both electron and muon lepton numbers do not add up. (c) Yes: $-1 \rightarrow -1 + 0$. (d) Yes: $0 \rightarrow 1 - 1$.

Q29 See diagram in answers in textbook.

Q30 (Not for option D) (a) It violates electron lepton number conservation. (b) It violates both electron and muon lepton number conservation. (c) It violates charge conservation. (d) It violates baryon number conservation. (e) It violates energy conservation and muon lepton number conservation. (f) It violates baryon number and electric charge conservation.

Q31 (Not for option D) The Higgs particle is a crucial ingredient of the standard model of particles. Its interactions with other particles make those particles acquire mass.