

Do all problems. They are of equal value. As usual the policy on late assignments (and other assignment related issues) can be found on the course website.

1. Griffiths 3.27 (for more practice with kinematics).

2. For the decays given below, draw one Feynman diagram for the decay and state what values of orbital angular momentum number ( $\ell$ ) are permitted in the final state. Explain your answers. You will need to look up the properties of the particles (quark content, spin, parity, isospin etc.) in the PDG listings. Note that, in a),  $J/\psi$  represents a single particle. The reason for the obscure symbol is historical.

a)  $B^0 \rightarrow J/\psi K_S^0$

b)  $\phi \rightarrow K^+ K^-$

c)  $\Delta^{++} \rightarrow p\pi^+$

d)  $D_s^- \rightarrow \phi\pi^-$

e)  $\Omega^- \rightarrow \Lambda^0 K^-$

f)  $K^{*0} \rightarrow K^0\gamma$

3. Through which isospin amplitude(s) may the following reactions proceed? Derive an expression for relations between the cross-sections for the three processes (at some fixed energy).

a)  $\pi^- + p \rightarrow \Sigma^0 + K^0$

b)  $\pi^- + p \rightarrow \Sigma^- + K^+$

c)  $\pi^+ + p \rightarrow \Sigma^+ + K^+$

4. The  $A_2$  meson has a mass of 1320 MeV and a width of 110 MeV and decays strongly via the decays

$$A_2 \rightarrow \pi^+\pi^-\pi^- \quad \text{and} \quad A_2 \rightarrow K^-K^0.$$

Discuss the possible assignments for the quantum numbers J (spin), P (parity), I (isospin) and S (strangeness) of this state. Explain your observations / conclusions.

5. As we discussed in class the ground state meson in any  $q\bar{q}'$  system has spin-0 and negative parity ( $J^P=0^-$ ). The next lightest state is the vector ( $J^P=1^-$ ) state in which the spins are aligned. The next four states come from the addition of one unit of orbital angular momentum.

a) What are the spin-parity assignments for these four states?

b) In the  $c\bar{u}$  system, only two of these four (so-called) orbitally-excited states have been observed experimentally, the  $D_1(2420)^0$  and the  $D_2^*(2460)^0$ , which have  $J^P=1^+$  and  $J^P=2^+$  respectively. The  $D_2^*(2460)^0$  decays strongly to either  $D^*\pi$  or  $D\pi$  while the  $D_1(2420)^0$  decays only to  $D^*\pi$ . Explain why both final states are allowed for the  $D_2^*(2460)^0$  while only the  $D^*\pi$  final state is open to the  $D_1(2420)^0$ .

[in each case, for the particles named above, the number represents the mass of the particle in  $\text{MeV}/c^2$ , the subscript denotes the spin  $J$ , and the final superscript denotes the charge. The presence of absence of a \* superscript is a convention that we don't need to understand for this question, though I will explain it in the solutions].

c) In the  $c\bar{s}$  system, the corresponding orbitally-excited states with  $J^P=1^+$  and  $J^P=2^+$ , the  $D_{s1}(2536)^+$  and the  $D_{s2}(2573)^+$ , decay to  $D^*K$  and  $DK$  final states rather than to final states with a lower mass  $c\bar{s}$  meson (for instance  $D_s\pi$  or  $D_s^*\pi$ ). Explain why this is the case.

d) The experimentally measured widths of the  $D_1(2420)^0$ ,  $D_2^*(2460)^0$ , and the  $D_{s2}(2573)^+$  are all of order  $20 \text{ MeV}/c^2$ . The  $D_{s1}(2536)^+$  on the other hand, has a width too small to be measured (the limit is  $< 2.3 \text{ MeV}/c^2$  at 90% confidence level). Explain this.

Note that parts b, c and d of this question are linked by the fact that we are discussing orbitally-excited charm mesons with one unit of orbital angular momentum ( $\ell = 1$ ), not by the physics that you need to consider for each part (which differs in each case).

6. Consider the scattering process  $e^+e^- \rightarrow XY$  where  $X$  and  $Y$  are hypothetical hadronic particles having the following properties:

$$M_X = 800 \text{ MeV}, \Gamma_X = 200 \text{ MeV} \quad Br(X \rightarrow \pi^+\pi^-) = 100\%$$

$$M_Y = 600 \text{ MeV}, \Gamma_Y = 50 \text{ MeV} \quad Br(Y \rightarrow \pi^0\pi^0) = 100\%$$

a) Which fundamental interaction is dominantly responsible for the decay of particle  $X$ ? What about particle  $Y$ ?

b) What can you say about the quark content of  $X$  and  $Y$ ? What about their spins?

Consider a large collection of such events (so that we can talk about distributions rather than the properties of individual events). If the initial state electron and positron have equal and opposite momenta of 2.0 GeV:

c) Sketch the invariant mass distribution of all  $\pi^+\pi^-$  combinations, and of all  $\pi^0\pi^0$  combinations.

d) Sketch the invariant mass distribution of all  $\pi^+\pi^-\pi^0\pi^0$  combinations.

e) Sketch the decay length distributions for particles  $X$  and  $Y$ . What are the mean decay lengths for each particle? [Don't overcomplicate this part. You can give a straightforward answer to this, or somewhat more complicated one. I'm happy if you give me the simple answer with a statement about what feature makes the reality a little bit more complicated.]

7. The lightest  $uds$  baryon is the  $\Lambda^0$  ( $J^P = 1/2^+$ ,  $M = 1115.7 \text{ MeV}$ ), which is an isospin singlet. The next lightest is the  $\Sigma^0$  ( $J^P = 1/2^+$ ,  $M = 1192.6 \text{ MeV}$ ), which is the neutral member of an isospin triplet. Its dominant decay is  $\Sigma^0 \rightarrow \Lambda^0\gamma$ . Explain why this is the case, and show that this decay can satisfy any conservation laws that are based on the information provided.