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1 Exercise

Use https://pdg.lbl.gov/ to determine what is the quark content of neutral vector mesons ρ^0, ω, ϕ, J/ψ?

These mesons can decay leptonically through a virtual photon, e.g. $V(q\bar{q}) \to \gamma \to e^+e^-$. The matrix element for this decay is proportional to $\langle\psi|\hat{Q}_q|\psi\rangle$, where ψ is the meson flavor wavefunction and $\hat{Q}_q$ is an operator proportional to the quark charge. Neglecting the relatively small differences in phase space, show that

$$\Gamma(\rho^0 \to e^+e^-) : \Gamma(\omega \to e^+e^-) : \Gamma(\phi \to e^+e^-) : \Gamma(J/\psi \to e^+e^-) \approx 9 : 1 : 2 : 8.$$

Discuss an experimental configuration to measure this process. What would change for different type of leptons in the decay (i.e. $\mu^+\mu^-$)?

2 Exercise

In an e^-p scattering experiment, the incident electron has energy $E_1 = 529.5$ MeV and the scattered electrons are detected at an angle $\theta = 75^\circ$ relative to the incoming beam.

(a) At this angle. almost all of the scattered electrons are measured to have an energy of $E_3 \approx 373$ MeV. What can be concluded from this observation?

(b) Find the corresponding value of Q^2.

3 Exercise

Consider the following process in the laboratory rest frame: $pp \to ppp\bar{p}$; i.e. a proton collides with a proton at rest, afterwards there should be one additional proton and one additional antiproton.

- How large is the threshold energy for this process in the center of mass frame, i.e. how large does the total energy of the protons need to be so this process can take place?
- How large is therefore the energy of the incident proton in the lab frame?

Mass of the proton is 938.3 MeV.

4 Exercise

The PEP2 storage ring (BABAR experiment) at the SLAC collides electrons e^- with an energy of 9.0 GeV with positrons e^+ with an energy of 3.1 GeV to produce a $B^0\bar{B}^0$ pair ($m_{B^0} = m_{\bar{B}^0} = 5.280$ GeV). The B^0 and the $\bar{B}^0$ have a lifetime of $\tau = 1.542 \times 10^{-12}$ s. How far do the B^0 and the $\bar{B}^0$ move between creation and decay (in the lab frame)?

5 Exercise

Tau leptons are produced in the process $e^+e^- \to \tau^+\tau^-$ at a centre-of-mass energy of 91.2 GeV. The angular distribution of the π^- from the decay $\tau^- \to \pi^-\nu_\tau$ is

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} \propto 1 + \cos\theta^*,$$

where θ^* is the polar angle of the π^- in the tau-lepton rest frame, relative to the direction defined by the τ spin. Determine the laboratory frame energy distribution of the π^- for the cases where the tau-lepton spin is (i) aligned with or (ii) opposite to its direction of flight.

6 Exercise

In a collider experiment, Λ baryons can be identified for the decay $\Lambda \to \pi^- p$, which gives rise to a displaced vertex in a tracking detector. In a particular decay, the momenta of the π^- and p are measured to be 0.75 GeV and 4.25 GeV respectively, and the opening angle between the tracks is 9°. The masses of the pion and proton are 139.6 MeV and 938.3 MeV.

- Calculate the mass of the Λ baryon.
- On average, Λ baryons of this energy are observed to decay at a distance of 0.35 m from the point of production. Calculate the lifetime of the Λ.

7 Exercise

Are the following processes possible? If yes, draw a diagram, if not - please explain why.
(a) $B^+ \to B^0 e^+$
(b) $K^0 \to \pi^- e^+ \nu_e$
(c) $n\nu_e \to p\pi^0 e^-$
(d) $\mu^+ p \to n\bar{\nu}_\mu \pi^+$

8 Exercise

Draw the Feynman diagrams of the lowest order for the following processes and determine the type of a transition (strong, weak, electromagnetic):
(a) $\bar{D}^0 \to \pi^+ e^- \bar{\nu}_e$
(b) $B^0 \to K^+ \pi^- \pi^0$
(c) $p\bar{p} \to K^- K^0 \pi^+$
(d) $\phi \to \mu^- \mu^+ e^- e^+$

9 Exercise

Explain why it is not possible to construct a valid Feynman diagram using the Standard Model vertices for the following processes:
(a) $\mu^- \to e^+ e^- e^+$,
(b) $\nu_\tau + p \to \mu^- + n$,
(c) $\nu_\tau + p \to \tau^+ + n$,
(d) $\pi^+(u\bar{d}) + \pi^-(d\bar{u}) \to n(udd) + \pi^0(u\bar{u})$.
Which of these processes would be the easiest to look for experimentally, and how?

10 Exercise

Draw the Feynman diagrams for the decays:
(a) $\Delta^+ \to n\pi^+$,
(b) $\Sigma^0 \to \Lambda\gamma$,
(c) $\pi^+ \to \mu^+ \nu_\mu$,
and place them in order of increasing lifetime.
How each of the decays can be measured experimentally?

11 Exercise

Treating the π^0 as a $u\bar{u}$ bound state, draw the Feynman diagrams for:
(a) $\pi^0 \to \gamma\gamma$,
(b) $\pi^0 \to \gamma e^+ e^-$,
(c) $\pi^0 \to e^+ e^- e^+ e^-$,
(d) $\pi^0 \to e^+ e^-$.

By considering the number of QED vertices present in each decay, estimate the relative decay rates taking $\alpha = 1/137$.

12 Exercise

Two particles $X^0(1192)$ and $Y^-(1311)$ are produced by the strong interaction:

$$K^- p \to \pi^0 X^0$$

$$K^- p \to K^+ Y^-$$

What is the quark content of the particles X^0 and Y^-?

These two particles decay as:

$$X^0 \to \Lambda\gamma$$

$$Y^- \to \lambda\pi^-$$

. Estimate the lifetime of these particles. Do these particles exist in nature?

13 Exercise

Using https://pdg.lbl.gov/, give the quark structure of the D_s^-, the mass, the lifetime and I(J^P). The same for $D{*}_s^-$.

Show that the process $D_s^{*-} \to D_s^- \pi^0$ is not possible via the strong interaction. Which interaction is responsible for this process? Draw the corresponding Feynman diagram.

A 3% branching ratio is found for $D_s^- \to \phi\pi^-$ with 59% $\phi \to K^- K^+$. Describe an experiment to study the D_s^{*-} properties.

14 Exercise

Positronium (PS) is a pseudo-atom, composited out of a positron e^+ and an electron e^-. It annihilates in two or three photons. Show that the processes:
$\pi^0 \to \gamma\gamma$
$P_s(^1S_0) \to \gamma\gamma$
$P_s(^3S_1) \to \gamma\gamma\gamma$
(spectroscopic notation $^{2s+1}L_J$) conserve the charge conjugation. Draw the corresponding Feynman diagrams. Discuss the energy spectrum, which we expect for the photons. Discuss an experimental configuration to study the 3 processes.

15 Exercise

Protonium is a state which consists out of a proton and an antiproton. We produce it by sending MeV antiprotons on the H_2 target. The antiproton captures with its field a proton and forms a protonic atom, the protonium. The protonium annihilates emitting hadrons (pions and kaons). Draw a diagram for the process $p\bar{p} \to \pi^+\pi^-$. What is the approximate total energy of the protonium? How does the energy spectrum for the pion in $p\bar{p} \to 2\pi$ look like? How does the spectrum look like in the case of $p\bar{p} \to 3\pi$? What equipment would you use to study these processes? How can you observe the evidence of: $p\bar{p} \to \rho + X$ with $\rho \to \pi^+\pi^-$?

Extra (if time permits):

Give the formula to calculate P and C of the $|p\bar{p}, L, S, I\rangle$ states. Consider the case $L = 0$. Show that the decay $p\bar{p} \to \pi^+\pi^-$ is excluded in the $^1S_0$ configuration. Show that the process only takes place in case of $^3S_1$ and $I = 1$.

16 Exercise

Describe briefly the discrete symmetries. A meson with spin J decays into $\pi^+\pi^-$. What is the value of C and P of the pion system?

Give the characteristics of the ρ meson. Why is $\rho^0 \to \pi^0\pi^0$ forbidden? Discuss an experimental configuration to study this processes.

17 Exercise

Describe briefly the discrete symmetries. For a system with two electrons in the state $|e^+, e^-, L, S\rangle$ which are the values of P, C.

Give the parameters of the ρ^0 meson. The decay $\rho \to e^+e^-$ is observed. Which kind of process is it? What are the possibility for the angular momentum L and the spin S for the two leptons? Compute the parity C of ρ^0. Discuss an experimental configuration to measure this process.

18 Exercise

Discuss the interaction of photons with matter. Consider photons with 1 MeV and photons with 1 GeV.

A π^0 with a momentum of 10 GeV/c decay into two photons. Estimate the maximum opening angle of the two photons in the laboratory frame. With the help of the corresponding empiric equation (see e.g. https://pdg.lbl.gov/), give the value for X_0 and E_C for a pure Pb detector. Calculate the Molière radius ρ_M. Imagine that the detector is 2 m away from the production point of the π^0. Are the two photons distinguishable before they reach the detector?

19 Exercise

Write the properties of the τ lepton. Write down the leptonic (i.e. without hadrons) decay modes. Draw a Feynman graph for such a decay. Suppose to produce a certain number of τ at rest in the laboratory and to observe the products of leptonic decays. Discuss (qualitatively) the shape of the spectrum of leptons. Could we deduce the mass of the τ lepton? What type of detector do you plan to perform this measurement?

20 Exercise

Write the properties of the τ lepton. Give a decay mode with two pions. Draw the corresponding Feynman graph. Consider e^+e^- collisions (LEP) with a centre of mass energy of 100 GeV, which produce $\tau^-\tau^+$ pairs. Draw the corresponding Feynman graph. What is the average mean free path of the τ until it decays. Which type of detector would be suited to measure the lifetime of the τ?

21 Exercise

Give the characteristics of the proton. How can we measure the magnetic dipole moment. Is the proton a Dirac particle? If we would see a different value for the antiproton, what would be the conclusion? Same question for the muon.

22 Exercise

Give the characteristics of the pion π^0. How can we determine the parity? What are the neutral decay modes of the pion? Why is there no decay with 3 photons? And what about a μ^+e^- channel?