Mid-Term

Elementary Particle Physics: Phys-4602
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Instructions: Examination for students registered in 4602 (undergraduate level). Attempt all questions. The mid-term exam counts for 25% of the term. The attached sheets have information you may find useful. No additional aids (textbooks, notes, calculators, tables) are permitted nor required.

1. In the Standard Model all matter is composed of quarks and leptons which interact via the exchange of gauge bosons. (5 pts)

   (a) What distinguishes quarks from leptons?

   (b) What are the mediators of the electromagnetic, weak, and strong interactions?

2. If $p\bar{p}$ annihilation at rest proceeds via S-wave states, explain why the reaction $p\bar{p} \to \pi^0\pi^0$ cannot be a strong interaction. (5 pts)

3. State which of the following particle reactions are allowed, and if the reaction is not allowed, explain why not (10 pts).

   (i) $\mu^+ \to e^+ + \gamma$

   (ii) $\Lambda^0 \to p + e^- + \bar{\nu}_e$

   (iii) $\Sigma^- \to \Lambda^0 + \pi^-$

   (iv) $\pi^- + p \to \pi^0 + \pi^0 + n$

   (v) $n + p \to K^+ + \pi^0 + \Lambda^0$

   (vi) $e^- + p \to e^- + \pi^+ + n$

   (vii) $K^- + p \to K^0 + \pi^+ + \Xi^-$

   (viii) $e^+ + e^- \to \mu^+ + \mu^-$

   (ix) $e^+ + e^- \to K^- + K^0 + \pi^+$

   (x) $\nu_e + p \to n + e^+ + \pi^0$

4. The deuteron is a bound state of two nucleus with total spin 1 and positive parity which may only exist in the $^{2S+1}L_J = {}^3S_1$ and ${}^3D_1$ states of the n-p system.

(a) Based on symmetry arguments, show that the isospin of the deuteron is $I = 0$. (5pts)

(b) Consider the proton scattering on deuteron. At a given centre-of-mass energy, what is the ratio of the cross-sections for the following strong reactions: (5 pts)

(1) $p + d \rightarrow \pi^0 + {}^3He$

(2) $p + d \rightarrow \pi^+ + {}^3H$

The nucleus ${}^3He$ and ${}^3H$ have the same quantum numbers than the proton and the neutron, respectively.

Leptons

$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix} \quad \begin{matrix} Q = -1 \\ Q = \ 0 \end{matrix} \tag{1}$$

Quarks

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \quad \begin{matrix} Q = +\frac{2}{3} \\ Q = -\frac{1}{3} \end{matrix} \tag{2}$$

Quark Mixing Matrix

$$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.975 & 0.221 & 0.004 \\ 0.221 & 0.974 & 0.043 \\ 0.004 & 0.043 & 0.999 \end{pmatrix} \tag{3}$$

Quark Model

$$Q = I_3 + Y/2\,, \tag{4}$$

where Q is the charge, I_3 is the $3^{\rm rd}$ isospin component, and $Y = B + S + C + \mathcal{B} + T$ is the hypercharge.

Quantity	Weak	E&M	Strong
Energy	yes	yes	yes
Charge	yes	yes	yes
Momentum	yes	yes	yes
Angular Momentum	yes	yes	yes
Baryon Number	yes	yes	yes
Lepton Number	yes	yes	yes
Isospin	no	no	yes
Strangeness	no	yes	yes

Table 1: Conservation Laws.

Particle	L_e	L_μ	L_τ	Q_ℓ	P	Mass (MeV)
e^-	+1	0	0	−1	+1	0.511
μ^-	0	+1	0	−1	+1	105.66
τ^-	0	0	+1	−1	+1	1784
ν_e	+1	0	0	0	+1	0
ν_μ	0	+1	0	0	+1	0
ν_τ	0	0	+1	0	+1	0

Table 2: Quantum numbers for leptons: L_ℓ is the lepton number, Q_ℓ is the charge, and P is the parity. For antileptons $L_{\bar{\ell}} = -L_\ell$, $Q_{\bar{\ell}} = -Q_\ell$, and $P_{\bar{\ell}} = -P_\ell$.

Particle	Quark Content	B	S	I	I_3	P	Mass (GeV)
p	uud	1	0	$\frac{1}{2}$	$\frac{1}{2}$	+1	0.938
n	udd	1	0	$\frac{1}{2}$	-$\frac{1}{2}$	+1	0.939
Δ^{++}	uuu	1	0	$\frac{3}{2}$	$\frac{3}{2}$	+1	1.230
Λ^0	uds	1	−1	0	0	+1	1.115
Σ^-	dds	1	−1	1	-1	+1	1.197
Ξ^-	dss	1	−2	$\frac{1}{2}$	-$\frac{1}{2}$	+1	1.321
Ω^-	sss	1	−3	0	0	+1	1.672
π^+	$u\bar{d}$	0	0	1	+1	−1	0.140
π^0	$u\bar{u}$ or $d\bar{d}$	0	0	1	0	−1	0.135
π^-	$\bar{u}d$	0	0	1	−1	−1	0.140
K^+	$u\bar{s}$	0	+1	$\frac{1}{2}$	$\frac{1}{2}$	−1	0.494
K^-	$\bar{u}s$	0	−1	$\frac{1}{2}$	-$\frac{1}{2}$	−1	0.494
$\bar{K}^0$	$\bar{d}s$	0	−1	$\frac{1}{2}$	$\frac{1}{2}$	−1	0.497
K^0	$d\bar{s}$	0	+1	$\frac{1}{2}$	-$\frac{1}{2}$	−1	0.497

Table 3: Quantum numbers for baryons and mesons: B is the baryon number, S is the strangeness, I is the isospin, I_3 is the 3^{rd} isospin component, P is the parity.