University of Durham

EXAMINATION PAPER

May/June 2014 Examination code: 043621/01

LEVEL 3 PHYSICS: FOUNDATIONS OF PHYSICS 3A

SECTION A. Quantum Mechanics 3
SECTION B. Nuclear and Particle Physics

Time allowed: 3 hours

Examination material provided: None

Calculators: The following types **only** may be used: Casio fx-83 GTPLUS or Casio fx-85 GTPLUS

Answer the compulsory question that heads each of sections A and B. These **two** questions have a total of 15 parts and carry 50% of the total marks for the paper. Answer **three** of the other questions with **at least one** from each section. If you attempt more than the required number of questions only those with the lowest question number compatible with the rubric will be marked: **clearly delete** those that are not to be marked. The marks shown in brackets for the main parts of each question are given as a guide to the weighting the markers expect to apply.

ANSWER EACH SECTION IN A SEPARATE ANSWER BOOK

Do **not** attach your answer booklets together with a treasury tag, unless you have used more than one booklet for a single section.

Information

Elementary charge:	$e = 1.60 \times 10^{-19}$ C
Speed of light:	$c = 3.00 \times 10^{8}\,\mathrm{m\,s^{-1}}$
Boltzmann constant:	$k_\mathrm{B} = 1.38 \times 10^{-23}\ \mathrm{J\,K^{-1}}$
Electron mass:	$m_\mathrm{e} = 9.11 \times 10^{-31}$ kg
Gravitational constant:	$G = 6.67 \times 10^{-11}\ \mathrm{N\,m^2\,kg^{-2}}$
Proton mass:	$m_\mathrm{p} = 1.67 \times 10^{-27}$ kg
Planck constant:	$h = 6.63 \times 10^{-34}$ J s
Permittivity of free space:	$\epsilon_0 = 8.85 \times 10^{-12}\ \mathrm{F\,m^{-1}}$
Magnetic constant:	$\mu_0 = 4\pi \times 10^{-7}\ \mathrm{H\,m^{-1}}$
Molar gas constant:	$R = 8.31\ \mathrm{J\,K^{-1}\,mol^{-1}}$
Avogadro's constant:	$N_\mathrm{A} = 6.02 \times 10^{23}\ \mathrm{mol^{-1}}$
Gravitational acceleration at Earth's surface:	$g = 9.81\ \mathrm{m\,s^{-2}}$
Stefan-Boltzmann constant:	$\sigma = 5.67 \times 10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}$
Astronomical Unit:	$\mathrm{AU} = 1.50 \times 10^{11}$ m
Parsec:	$\mathrm{pc} = 3.09 \times 10^{16}$ m
Solar Mass:	$M_\odot = 1.99 \times 10^{30}$ kg
Solar Luminosity:	$L_\odot = 3.84 \times 10^{26}$ W

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SECTION A. QUANTUM MECHANICS 3

Answer Question 1 and **at least one** of Questions 2 and 3.

1. (a) Briefly explain how to use the Rayleigh-Ritz variational method to obtain an approximate value of the ground state energy of a quantum system. [4 marks]

   (b) Consider a cavity containing atoms (of a single kind) and radiation, in thermal equilibrium at an absolute temperature T. Each atom can be either in a state a of energy E_a or a state b of energy $E_b > E_a$. Neither E_a nor E_b is degenerate. We denote the number of atoms in state a and state b at time t by, respectively, $N_a(t)$ and $N_b(t)$, and the energy density of the radiation at the angular frequency $\omega_{ba} = (E_b - E_a)/\hbar$ by $\rho(\omega_{ba})$. Thus

$$\frac{dN_a}{dt} = N_b(t)B_{ab}\rho(\omega_{ba}) - N_a(t)B_{ba}\rho(\omega_{ba}) + N_b(t)A_{ab},$$

   where B_{ab}, B_{ba} and A_{ab} are three constant coefficients.

   (i) Show that $B_{ba} = B_{ab}$ and that $A_{ab} = \hbar\omega_{ba}^3 B_{ab}/(\pi^2 c^3)$. [2 marks]

   (ii) How is A_{ab} related to the lifetime of the state b? [2 marks]

   [Hint: In thermal equilibrium, $N_a(t)/N_b(t) = \exp[\hbar\omega_{ba}/(k_{\mathrm{B}}T)]$ and
$$\rho(\omega_{ba}) = \frac{\hbar\omega_{ba}^3}{\pi^2 c^3}\,\frac{1}{\exp[\hbar\omega_{ba}/(k_{\mathrm{B}}T)] - 1}.$$
   ]

   (c) Which of the following states, if any, could the $(n = 5, l = 2, m = 0)$ state of atomic hydrogen decay to spontaneously according to the electric dipole selection rules? Specify which rule(s) forbid the transition if the transition is not allowed. You may ignore the fine structure of the levels. (i) $(n = 4, l = 0, m = 0)$. (ii) $(n = 4, l = 1, m = 0)$. (iii) $(n = 4, l = 2, m = 0)$. (iv) $(n = 4, l = 3, m = 0)$. (v) $(n = 4, l = 3, m = 1)$. (vi) $(n = 4, l = 3, m = 2)$.[4 marks]

   (d) What are the values of the orbital quantum number L, of the spin quantum number S and of the total angular momentum quantum number J in a $^7\mathrm{S}_3$ state? What are the possible values of M_S, the spin magnetic quantum number, in that state? [4 marks]

   (e) (i) What should the angular frequency of the perturbation be for a resonance to occur in a quantum system subjected to a perturbation varying sinusoidally in time? (ii) Write down the electric dipole operator of a one-electron atom. (iii) What is an intercombination line, in relation to radiative transitions among the energy levels of complex atoms? [4 marks]

   (f) What is the Born-Oppenheimer approximation, in relation to the calculation of the wave functions and energy levels of molecules? [4 marks]

2. A time-independent Hamiltonian, H_0, is perturbed by a time-dependent perturbation, $H'(t)$, such that $H'(t) \equiv 0$ for $t < 0$. The system for which $H_0 + H'(t)$ is the total Hamiltonian is in the eigenstate a of H_0 for $t < 0$. In first order perturbation theory, the probability $P_{ba}(t)$ that it is in the state b of H_0 at time $t > 0$ is given by the following equation, assuming that $\omega_{ba} \neq 0$:

$$P_{ba}(t) = \frac{1}{\hbar^2} \left| \int_0^t H'_{ba}(t') \exp(i\omega_{ba} t') dt' \right|^2 ,$$

where $\omega_{ba} = (E_b - E_a)/\hbar$, with E_a and E_b the eigenenergies of the states a and b, respectively.

(a) Define the quantity $H'_{ba}(t')$ appearing in this equation in terms of eigenstates of H_0. [2 marks]

(b) An electron, at rest, is exposed to a magnetic field $\underline{\mathcal{B}}$. The field changes in strength and direction at $t = 0$, such that $\underline{\mathcal{B}} = \mathcal{B}_z \underline{\hat{z}}$ for $t < 0$ and $\underline{\mathcal{B}} = \mathcal{B}_x \underline{\hat{x}} + \mathcal{B}_z \underline{\hat{z}}$ for $t > 0$, where $\underline{\hat{x}}$ and $\underline{\hat{z}}$ are the unit vectors in, respectively, the x- and z-directions and $\mathcal{B}_x$ and $\mathcal{B}_z$ are two real constants ($|\mathcal{B}_x| \ll |\mathcal{B}_z|$). Correspondingly, the Hamiltonian of the electron is $g\mu_{\mathrm{B}} \underline{B} \cdot \underline{S}/\hbar$, where $\underline{S}$ is the spin operator, g is the gyromagnetic ratio of the electron, and μ_{B} is the Bohr magneton.

(i) Let $|\uparrow\rangle$ and $|\downarrow\rangle$ represent the states of spin-up and spin-down, respectively, i.e. $S_z|\uparrow\rangle = (\hbar/2)|\uparrow\rangle$ and $S_z|\downarrow\rangle = (-\hbar/2)|\downarrow\rangle$. If the electron is in the spin-down state at $t < 0$, the probability $P_{\uparrow\downarrow}(t)$ that it is in the spin-up state at a time $t > 0$ oscillates between 0 and a maximum value $P_{\uparrow\downarrow}^{\max}$. Show that in first order perturbation theory $P_{\uparrow\downarrow}^{\max} = \mathcal{B}_x^2/\mathcal{B}_z^2$. [12 marks]

(ii) At what angular frequency does $P_{\uparrow\downarrow}(t)$ oscillate, as predicted by first order perturbation theory? [1 mark]

(iii) Explain why one can expect that the angular frequency predicted by first order perturbation theory differs from the exact angular frequency by a factor $[\mathcal{B}_z^2/(\mathcal{B}_x^2 + \mathcal{B}_z^2)]^{1/2}$. [5 marks]

$$\left[\text{Hint:} \quad S_x \equiv \frac{\hbar}{2} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad S_z \equiv \frac{\hbar}{2} \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.\right]$$

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3. (a) Explain why neither $u_{1s\uparrow}(q_1)u_{1s\downarrow}(q_2)$ nor $[u_{1s\uparrow}(q_1)u_{1s\downarrow}(q_2)+u_{1s\downarrow}(q_1)u_{1s\uparrow}(q_2)]/\sqrt{2}$ could represent the ground state wave function of helium, even approximately. (The functions $u_{1s\uparrow}(q)$ and $u_{1s\downarrow}(q)$ represent one-electron spin-orbitals of, respectively, spin up and spin down, and q_1 and q_2 denote the spatial and spin variables of, respectively, electron 1 and electron 2.) [4 marks]

(b) A system of two electrons is in the state represented by the wave function

$$R_p(r_1)R_p(r_2)[Y_{10}(\theta_1,\phi_1)Y_{11}(\theta_2,\phi_2) - Y_{11}(\theta_1,\phi_1)Y_{10}(\theta_2,\phi_2)]\chi(1,2)/\sqrt{2},$$

where $\chi(1,2)$ is a spin function representing the joint spin state of the two electrons, (r_1,θ_1,ϕ_1) and (r_2,θ_2,ϕ_2) are the spherical polar coordinates of the two electrons, $R_p(r)$ is the radial function of a p-orbital, and $Y_{lm}(\theta,\phi)$ denotes a spherical harmonic of orbital angular momentum quantum number l and magnetic quantum number m. Show that this wave function describes a $L = 1$, $S = 1$ state of even parity, with L and S the total orbital and spin angular momentum quantum numbers of the system. [12 marks]

[Hint: With L_{1x}, L_{1y} and L_{1z} denoting the x-, y- and z-components of the orbital angular momentum operator for electron 1, $\underline{L}_1$,
$L_{1x}Y_{10}(\theta_1,\phi_1) = \hbar[Y_{11}(\theta_1,\phi_1) + Y_{1-1}(\theta_1,\phi_1)]/\sqrt{2}$,
$L_{1y}Y_{10}(\theta_1,\phi_1) = -i\hbar[Y_{11}(\theta_1,\phi_1) - Y_{1-1}(\theta_1,\phi_1)]/\sqrt{2}$,
$L_{1z}Y_{10}(\theta_1,\phi_1) = 0$,
$L_{1x}Y_{11}(\theta_1,\phi_1) = \hbar Y_{10}(\theta_1,\phi_1)/\sqrt{2}$,
$L_{1y}Y_{11}(\theta_1,\phi_1) = i\hbar Y_{10}(\theta_1,\phi_1)/\sqrt{2}$,
$L_{1z}Y_{11}(\theta_1,\phi_1) = \hbar Y_{11}(\theta_1,\phi_1)$,
and similarly for the x-, y- and z-components of the orbital angular momentum operator for electron 2, $\underline{L}_2$. Note also that if $\underline{L} = \underline{L}_1 + \underline{L}_2$, then $\underline{L}^2 = \underline{L}_1^2 + \underline{L}_2^2 + 2L_{1x}L_{2x} + 2L_{1y}L_{2y} + 2L_{1z}L_{2z}$.]

(c) What is the largest possible value of S (i) for an atom of carbon ($Z = 6$) in the configuration $(1s)^2(2s)^2(2p)^2$, (ii) for an atom of oxygen ($Z = 8$) in the configuration $(1s)^2(2s)^2(2p)^4$? [4 marks]

SECTION B. NUCLEAR AND PARTICLE PHYSICS

Answer Question 4 and **at least one** of Questions 5, 6, 7 and 8.

4. (a) A stationary tau lepton decays producing the ρ^- meson and the tau neutrino. The tau lepton, rho meson and neutrino have masses m_τ, m_ρ and zero, respectively. Find an expression for the energy of the ρ^- meson in terms of the particle masses. [4 marks]

(b) List four properties of the nuclear force. [4 marks]

(c) A nucleon-nucleon system has isospin and total spin quantum numbers I and S and an orbital angular momentum quantum number $\ell = 0$. Use the symmetry of the wavefunction to show that $S + I$ must be odd. [4 marks]

(d) An excited nucleus can decay to the ground state, which has $J^P = \frac{3}{2}^+$, by an electric quadrupole transition. Given that this is the most likely transition what are the spin and parity of the excited state? [4 marks]

(e) The Ω^- baryon contains three valence strange quarks and has spin $\frac{3}{2}$. Use the symmetry of the Ω^- wavefunction to explain why the colour quantum number is required. [4 marks]

(f) The a_1^+ meson ($J^P = 1^+$) decays via the strong force producing the ρ^+ ($J^P = 1^-$) and π^0 ($J^P = 0^-$) mesons. What are the allowed values of the orbital angular momentum quantum number for the ρ^+-π^0 system produced in the decay? [4 marks]

(g) Draw the leading-order Feynman diagram for the decay of the muon to the muon neutrino, electron and antielectron neutrino. Using the Feynman diagram and dimensional analysis explain why $\Gamma \propto m_\mu^5$, where Γ is the decay rate of the muon and m_μ is the mass of the muon. The mass of the electron can be neglected. [4 marks]

(h) The Breit-Wigner cross section for $e^+e^- \to Z^0 \to f\bar{f}$ is

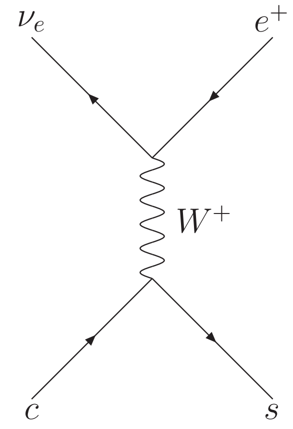
$$\sigma(e^+e^- \to Z^0 \to f\bar{f})(s) = 12\pi \frac{\Gamma_{Z^0\to e^+e^-}\Gamma_{Z^0\to f\bar{f}}}{(s - M_Z^2)^2 + M_Z^2\Gamma_{Z\ \mathrm{total}}^2},$$

where s is the centre-of-mass energy squared, M_Z is the mass of the Z^0 boson, $\Gamma_{Z\ \mathrm{total}}$ is the total width of the Z^0 boson, and $\Gamma_{Z^0\to e^+e^-}$ and $\Gamma_{Z^0\to f\bar{f}}$ are the partial widths for the decay of the Z^0 boson into e^+e^- and $f\bar{f}$, respectively. The cross section $\sigma(e^+e^- \to \mathrm{hadrons})(M_Z^2) = 39\,\mathrm{nb}$. Calculate the branching ratio for the Z^0 boson to decay into neutrinos assuming lepton universality, (that is that the branching ratios for the decay of the Z^0 boson into e^+e^-, $\mu^+\mu^-$ and $\tau^+\tau^-$ are equal) with $B(Z^0 \to e^+e^-) = 0.033$. [4 marks]

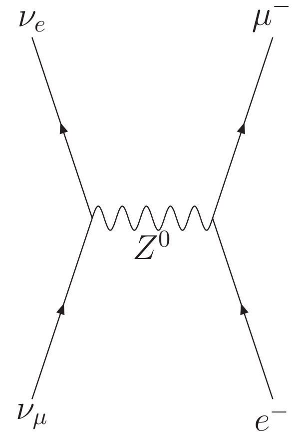
[Hint: $(\hbar c)^2 = 0.389\,\mathrm{GeV}^2\mathrm{mb}$, M_Z=91.18 GeV.]

(i) Identify, with reasons, which of the following processes are forbidden. For the allowed processes indicate whether the interaction is weak, electromagnetic or strong.

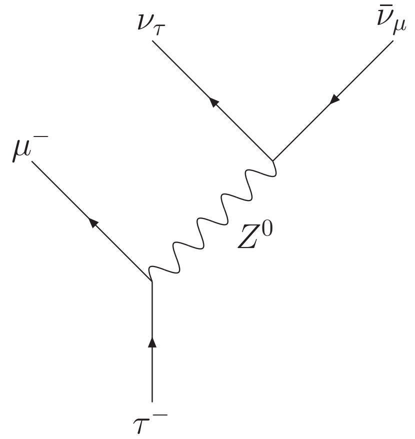
i)



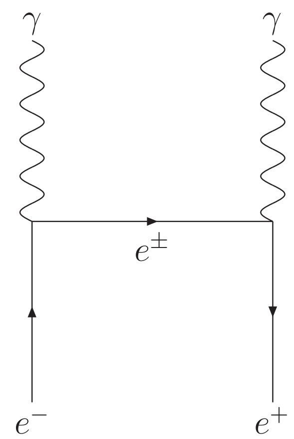
ii)



iii)



iv)



[4 marks]

5. The semi-empirical mass formula predicts that the nuclear binding energy, B, for a nucleus with mass number A, atomic number Z and neutron number N is

$$B = a_V A - a_S A^{\frac{2}{3}} - a_c \frac{Z^2}{A^{\frac{1}{3}}} - a_a \frac{(N-Z)^2}{4A} - \frac{\delta}{A^{\frac{1}{2}}}$$

where $a_V = 15.27\,\mathrm{MeV}$, $a_S = 16.7\,\mathrm{MeV}$, $a_c = 0.72\,\mathrm{MeV}$, $a_a = 86\,\mathrm{MeV}$ and

$$\delta = \begin{cases} -11.8\,\mathrm{MeV} & \text{for even } Z \text{ and } N \text{ (even} - \text{even nuclei)}, \\ 0\,\mathrm{MeV} & \text{for odd } A \quad \text{(odd} - \text{even nuclei)}, \\ 11.8\,\mathrm{MeV} & \text{for odd } Z \text{ and } N \text{ (odd} - \text{odd nuclei)}. \end{cases}$$

a) Neglecting the pairing term, $\delta/A^{\frac{1}{2}}$, show that the most stable nucleus with mass number A has atomic number Z given by

$$\frac{Z}{A} = \frac{m_\mathrm{n} - m_\mathrm{p} + a_a}{2\left(a_a + a_c A^{\frac{2}{3}}\right)}.$$

[4 marks]

b) What is the most the stable isotope for $A = 75$? [2 marks]

In the following parts of this question you may assume that the pairing term can be neglected and that the result of part a) can be approximated by $Z = \lambda A$ with $\lambda = 0.43$.

c) What is the minimum value of A for which spontaneous fission into two fragments with equal atomic and mass numbers is energetically possible? [4 marks]

d) Assuming A is large what is the minimum value of A for which the most stable nucleus can undergo α decay? The binding energy of ${}^4_2\mathrm{He}$ is 28.3 MeV [8 marks]

e) Briefly explain whether spontaneous fission or α decay is more likely in general. [2 marks]

[Hint: $(m_\mathrm{n} - m_\mathrm{p}) = 1.294\,\mathrm{MeV}$, $m_\mathrm{p} = 938.3\,\mathrm{MeV}$, $m_\mathrm{e} = 0.511\,\mathrm{MeV}$.]

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6. In the absence of spin-orbit interactions the first five energy levels for protons or neutrons in a nucleus, labelled by their orbital angular momenta, are $1s$, $1p$, $2s$, $1d$ and $1f$. These energy levels are split by a spin-orbit coupling

$$V(r) = V_{\ell s}(r)\langle \underline{l} \cdot \underline{s} \rangle,$$

where $\underline{\ell}$ is the orbital angular momentum, $\underline{s}$ the spin angular momentum and the associated quantum numbers are ℓ and s, respectively. The expectation value of the spin-orbit potential $V_{\ell s}(r)$ is negative.

a) Determine the splitting of the energy levels with total angular momentum quantum number $j = \ell + s$ and $j = |\ell - s|$ due to spin orbit coupling, where $s = \frac{1}{2}$. [4 marks]

b) Sketch the energy levels which result from the spin-orbit coupling, giving the j quantum numbers of the levels, the number of nucleons that may occupy each level and the first four magic numbers. [4 marks]

[Hint: After spin-orbit coupling the lower energy level from the splitting of the $1d$ energy level has lower energy than the $2s$ level.]

c) Calculate the spin and parity of the ground state for the following nuclei:

$${}^{5}_{2}\mathrm{He}; \quad {}^{25}_{12}\mathrm{Mg}; \quad {}^{36}_{18}\mathrm{Ar}; \quad {}^{43}_{21}\mathrm{Sc};$$

in the single-particle shell model. [4 marks]

d) The first excited state of ${}^{17}_{8}\mathrm{O}$ decays to the ground state of ${}^{17}_{8}\mathrm{O}$ by emitting a photon in an electric quadrupole transition. No electric or magnetic dipole transitions to the ground state from the first excited state are observed. What is the most likely spin and parity of this level in the shell model and in which energy level is the unpaired nucleon? [4 marks]

e) The binding energies of the silicon isotopes ${}^{27}_{14}\mathrm{Si}$, ${}^{28}_{14}\mathrm{Si}$ and ${}^{29}_{14}\mathrm{Si}$ are 219.36, 236.54 and 245.01 MeV, respectively. Calculate the separation of the $2s_{\frac{1}{2}}$ and $1d_{\frac{5}{2}}$ energy levels for nuclei with mass number $A \approx 28$. [4 marks]

7. Consider the charged current deep inelastic scattering process $\nu_\mu(k) + N(P) \to \mu^-(k') + X(P')$, where N is a nucleon, X denotes a system of hadrons and the four momenta of the particles are given in brackets. The nucleon is initially at rest, the energy of the neutrino is E, the muon E' and mass of the muon may be neglected. The kinematic variables

$$q = k - k', \qquad Q^2 = -q^2, \quad \text{and} \quad x = \frac{Q^2}{2P \cdot q},$$

are used to describe the scattering process.

a) Calculate the centre-of-mass energy squared s and the mass squared W^2 of the system X. Hence show that for elastic scattering ($X = N$), $Q^2 = 2M(E - E')$. [5 marks]

b) Draw the Feynman diagrams for the quark-level processes which contribute to neutrino-nucleon scattering and the corresponding antineutrino-nucleon scattering process $\bar{\nu}_\mu(k) + N(P) \to \mu^+(k') + X(P')$. [4 marks]

The cross sections for the scattering of a neutrino from a down quark (antineutrino from a down antiquark) and a neutrino from an up antiquark (antineutrino from an up quark) are:

$$\sigma(\nu_\mu d) = \sigma(\bar{\nu}_\mu \bar{d}) = \frac{G_F^2 x s}{\pi}; \qquad \sigma(\nu_\mu \bar{u}) = \sigma(\bar{\nu}_\mu u) = \frac{G_F^2 x s}{3\pi},$$

where G_F is the Fermi constant. Assume that the nucleons only contain up and down quarks, and their corresponding antiquarks.

c) Show that the parton model predicts that the average cross sections for neutrino-nucleon and antineutrino-nucleon scattering are

$$\begin{aligned} \sigma(\nu_\mu N) = \frac{1}{2}\left(\sigma(\nu_\mu p) + \sigma(\nu_\mu n)\right) &= \frac{G_F^2 s}{2\pi}\left[f_q + \frac{1}{3} f_{\bar{q}}\right], \\ \sigma(\bar{\nu}_\mu N) = \frac{1}{2}\left(\sigma(\bar{\nu}_\mu p) + \sigma(\bar{\nu}_\mu n)\right) &= \frac{G_F^2 s}{2\pi}\left[\frac{1}{3} f_q + f_{\bar{q}}\right], \end{aligned}$$

where $f_q = f_u + f_d$ and $f_{\bar{q}} = f_{\bar{u}} + f_{\bar{d}}$ are the average momentum fractions carried by the up and down quarks and antiquarks, respectively. [6 marks]

d) Experimentally, for $E \gg M$,

$$\frac{\sigma(\nu_\mu N)}{E_\nu} = 0.43 \frac{G_F^2 M}{\pi} \qquad \text{and} \qquad \frac{\sigma(\nu_{\bar{\mu}} N)}{E_{\bar{\nu}}} = 0.21 \frac{G_F^2 M}{\pi}.$$

Calculate f_q and $f_{\bar{q}}$ and comment on the physical significance of your result. [5 marks]

8. The baryons which contain two strange quarks and one up (u) or down (d) quark are denoted $\Xi^0(ssu)$ and $\Xi^-(ssd)$.

   a) What are the possible spins, S_{ss}, of the pair of strange quarks in each of these baryons? Use the spins of the strange quark pairs to obtain the possible spins of the baryons and hence determine the number of $\Xi^{-,0}$ states and their spins. [4 marks]

   b) Show that for a ground-state baryon with total angular-momentum J

$$\sum_{\substack{i,j=1\\i<j}}^{3} \underline{s}_i \cdot \underline{s}_j = \frac{1}{2}\left[J(J+1) - \frac{9}{4}\right].$$

   [2 marks]

The hyperfine mass splitting for baryons is

$$\Delta M_{ss} = \frac{16}{9}\pi\alpha_S\,|\psi(0)|^2 \sum_{\substack{i,j=1\\i<j}}^{3} \frac{\underline{s}_i \cdot \underline{s}_j}{m_i m_j},$$

where the sum is over the three quarks in the baryon, and $\underline{s}_i$ and m_i are the spin and the constituent mass of the quark, respectively. Here $|\psi(0)|^2$ is the probability that the two quarks are at the same point in space and α_S is the strong coupling.

   c) Calculate the masses of the $\Xi^{-,0}$ states given that the constituent masses of the up/down and strange quarks are $m_{u,d} = 363\,\mathrm{MeV}$ and $m_s = 538\,\mathrm{MeV}$, respectively, and $\pi\alpha_S|\psi(0)|^2 = 1.6\times10^7\,\mathrm{MeV}^3$. [9 marks]

   d) The masses of the lightest baryons containing one strange quark, in MeV, are:

$$\Lambda^0(uds)\ \ 1116; \quad \Sigma^+(uus)\ \ 1189; \quad \Sigma^0(uds)\ \ 1193; \quad \Sigma^-(dds)\ \ 1197;$$

   where Λ^0 has isospin zero and the Σ baryons form an isospin one triplet. The mass of the kaons, K^- ($|s\bar{u}\rangle$) and $\bar{K}^0$ ($|s\bar{d}\rangle$), are 496 MeV and the mass of the pions, $\pi^+(|u\bar{d}\rangle)$, $\pi^-(|d\bar{u}\rangle)$ and $\pi^0\left(\frac{1}{\sqrt{2}}(|u\bar{u}\rangle + |d\bar{d}\rangle)\right)$, are 140 MeV.

   Determine how the Ξ^0 baryons decay and draw quark-line diagrams for these processes. [5 marks]

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