UNIVERSITY OF CAMBRIDGE

NATURAL SCIENCES TRIPOS Part II

Friday 3 June 2011 9.00 am to 10.30 am

EXPERIMENTAL AND THEORETICAL PHYSICS (3A)
PHYSICAL SCIENCES: HALF SUBJECT PHYSICS (3A)

Candidates offering this paper should attempt a total of **three** *questions. The questions to be attempted are* **1**, **2** *and* **one** *other question.*

The approximate number of marks allocated to each question or part of a question is indicated in the right margin. This paper contains **4** *sides, and is accompanied by a handbook giving values of constants and containing mathematical formulae which you may quote without proof.*

STATIONERY REQUIREMENTS	SPECIAL REQUIREMENTS
20 Page Answer Book	Mathematical Formulae handbook
Metric graph paper	Approved calculator allowed
Rough workpad	
Yellow master coversheet	

You may not start to read the questions printed on the subsequent pages of this question paper until instructed that you may do so by the Invigilator.

PARTICLE AND NUCLEAR PHYSICS

1 *Attempt* **all** *parts of this question. Answers should be concise, and relevant formulae may be assumed without proof.*

(a) The baryons Λ^0 and Σ^0 have the same quark composition (uds) and both are members of the same $J^P = \frac{1}{2}^+$ baryon octet. Explain why their masses are different (1.116 GeV and 1.193 GeV respectively), and suggest why their lifetimes are very different (2.6×10^{-10} s and 7×10^{-20} s respectively). [4]

(b) In the nuclear shell model, the lowest-lying nucleon energy levels are, in order of increasing energy:

$$1s_{\frac{1}{2}},\ 1p_{\frac{3}{2}},\ 1p_{\frac{1}{2}},\ 1d_{\frac{5}{2}},\ \ldots\ .$$

Predict the spin and parity of the ground states of the following nuclides:

$$^{15}_{7}\mathrm{N};\ \ ^{6}_{2}\mathrm{He};\ \ ^{19}_{10}\mathrm{Ne}\ .$$ [4]

(c) If the Fermi coupling constant is derived from measurements of the β-decay of the muon, the value obtained is $\sim 2.6\%$ greater than that obtained from nuclear β-decay. Why? [4]

2 *Attempt this question. Credit will be given for well-structured and clear explanations, including appropriate diagrams and formulae. Detailed mathematical derivations are not required.*

Write brief notes on **two** of the following: [13]

(a) charmonium and bottomonium;

(b) neutrino oscillations;

(c) nuclear fusion and its applications.

3 *Attempt* **either** *this question* **or** *question 4.*

Draw the (three) leading-order Feynman diagrams for the process

$$e^+e^- \longrightarrow W^+W^- \quad . \qquad [3]$$

It is proposed to study this process using a positron beam incident on a fixed target containing electrons. What minimum energy is needed for the positron beam? The mass of the W-boson can be taken to be 80.4 GeV, and you may neglect its width. [4]

In the rest of the question, the process is instead studied using 100 GeV beams of electrons and positrons colliding head on. Show that the W-bosons are produced with momenta 59.5 GeV. [1]

One of the possible decay modes of the W-boson is $W^+ \to e^+\nu_e$. Estimate the branching ratio for this decay, explaining your assumptions carefully. [6]

Considering the decay mode $W^+ \to e^+\nu_e$, and making the assumption that the W-bosons are produced unpolarised, show that the e^+ observed in the centre-of-mass frame of the collision should have a uniform distribution of energies, and compute the minimum and maximum energies of the e^+. [5]

The total decay width of the W-boson is 2.1 GeV. What is its mean lifetime? How far, on average, will each W-boson travel before decaying? [3]

Compare the typical separation between the W-bosons when they decay with the range of the strong interaction. What implications might this have in the case where both W-bosons decay to hadronic final states? [3]

[*You may use* $\hbar = 6.6 \times 10^{-25}$ GeV s.]

4 *Attempt* **either** *this question* **or** *question 3.*

The Semi-Empirical Mass Formula (SEMF) for nuclear masses may be written in the form

$$M(A, Z) = Zm_\mathrm{p} + (A - Z)m_\mathrm{n} - a_\mathrm{V}A + a_\mathrm{S}A^{\frac{2}{3}} + a_\mathrm{C}\frac{Z^2}{A^{\frac{1}{3}}} + a_\mathrm{A}\frac{(A - 2Z)^2}{A} + \delta(A, Z)\,,$$

where m_p and m_n are the masses of the proton and neutron respectively, and the other symbols have their conventional meanings. Fitted values for the coefficients are given at the end of the question. Explain the physical significance and functional form of the various contributions to the binding energy. [9]

Consider fission of a nucleus $[A, Z]$ into fragments $[\alpha A, \alpha Z]$ and $[(1 - \alpha)A, (1 - \alpha)Z]$. Use the SEMF (neglecting the $\delta(A, Z)$ term) to find an expression for the energy release E_0 in such a fission process. [4]

Show that the maximum energy release occurs for $\alpha = \frac{1}{2}$ and that this maximum energy release is:

$$E_0^{\max} = -0.260 a_\mathrm{S}A^{\frac{2}{3}} + 0.370 a_\mathrm{C}\frac{Z^2}{A^{\frac{1}{3}}} \quad .$$

Hence estimate the mimimum value of Z^2/A for which fission should be energetically possible. [5]

Why in practice is spontaneous fission only observed for much heavier nuclei? [2]

Find an expression for the energy difference between the nucleus $[A, Z]$ and two nuclei $[\frac{1}{2}A, \frac{1}{2}Z]$ when the daughter nuclei are just touching at their surfaces. Use this to estimate the value of Z^2/A above which spontaneous fission should be instantaneous. [5]

[*You may use the following data:* $m_\mathrm{p} = 938.3\,\mathrm{MeV}$, $m_\mathrm{n} = 939.6\,\mathrm{MeV}$, $a_\mathrm{V} = 15.8\,\mathrm{MeV}$, $a_\mathrm{S} = 18.0\,\mathrm{MeV}$, $a_\mathrm{C} = 0.72\,\mathrm{MeV}$, $a_\mathrm{A} = 23.5\,\mathrm{MeV}$. *Nuclear radius* $R = R_0A^{1/3}$ *with* $R_0 = 1.2\,\mathrm{fm}$.]

END OF PAPER