	Candidate No. ....
UNIVERSITY COLLEGE LONDON	Seat No. ....

EXAMINATION FOR INTERNAL STUDENTS

MODULE CODE	:	**PHAS3224**
ASSESSMENT PATTERN	:	**PHAS3224A**
MODULE NAME	:	**Nuclear and Particle Physics**
DATE	:	**09 May 2017**
TIME	:	**10:00 am**
TIME ALLOWED	:	**2 hours 30 mins**

This paper is suitable for candidates who attended classes for this module in the following academic year(s):

2014/2015, 2015/2016, 2016/2017

<u>Under no circumstances</u> are the attached papers to be removed from the examination by the candidate.

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TURN OVER

Answer ALL questions from Section A and TWO questions from Section B
Only two answers on Section B will be marked

The numbers in square brackets in the right-hand margin indicate the provisional allocation of maximum marks per sub-section of a question.

Numerical Data

Useful particle masses are given in the following table:

	Mass [MeV/c^2]
Neutrinos	< 0.0001
Electron	0.5
down-quark	3
up-quark	5
strange-quark	100
muon	106
charm-quark	1300
tau	1780
bottom-quark	4500
top-quark	173000

END OF NUMERICAL DATA

Section A

[Part marks]

1. List all the fundamental bosons in the Standard Model indicating the electric charge and spin of each. [8]

2. (a) What is a jet in particle physics? [2]

   (b) Explain how the process $e^+e^- \to q\bar{q}$ in an e^+e^- collider leads to the production of two jets. [4]

3. In a Deep Inelastic Scattering experiment electrons are scattered off protons. Derive an expression for $Q^2 = -q^2$, where q^2 is the four-momentum transfer of the interaction, in terms of the energy of the incoming electron, E, the energy of the outgoing electron, E' and the electron scattering angle, θ. You may neglect the mass of the electron. [6]

4. Consider a muon produced at the centre of a typical collider detector.
   Name the sub-detectors through which a radially outward moving muon would pass. [4]
   Which subdetectors measure the momentum of the muon? [2]

5. What is an isotope? [2]
   What evidence led to the formulation of the nuclear shell model? [2]
   Which two particles are emitted in β^+ decay? [2]
   Name two other radioactive decay processes. [2]

6. Consider particles passing through a detector.
   List two processes by which photons lose energy. [2]
   What is the dominant process for muons to lose energy? [1]
   Which loses more energy when passing through a thin absorber: a muon with a kinetic energy of 10 MeV or a muon with a kinetic energy of 500 MeV? [1]
   In which material are electromagnetic cascades shorter: natural xenon $^{132}_{54}$Xe or diamond $^{12}_{6}$C? Explain why. [2]

Section B

[Part marks]

Please answer two questions from this section.
Note that only two answers from Section B will be marked

7. (a) Consider the process $e^+e^- \to \mu^+\mu^-$. Draw and label the Feynman diagram that dominates in the low centre-of-mass region and the Feynman diagram that dominates in the region around 91 GeV. [6]

   (b) Calculate the ratio of the cross section for $e^+e^- \to u\bar{u}$ to that for $e^+e^- \to \mu^+\mu^-$ for a centre-of-mass energy well below 91 GeV. You may neglect the effect of fermion masses. [5]

   (c) Consider the process $u\bar{u} \to Z \to \mu^+\mu^-$ at the LHC. If the Z boson is produced with a mass 91 GeV/c^2 and a momentum of +10 GeV/c in the direction of the beam, what is the value of x_1 and x_2, where x_1 is the proton momentum fraction carried by the up-quark, u, and x_2 is the proton momentum fraction carried by the antiup-quark, $\bar{u}$. The energy of each LHC beam is 6500 GeV and the u quark in the interaction comes from the proton travelling with a positive momentum. You may neglect the masses of the quarks. [10]

   (d) In 1957 Wu and collaborators studied the β decay of polarised Cobalt-60: $^{60}\text{Co} \to {}^{60}\text{Ni}^* + e^- + \bar{\nu}_e$. Explain what they observed and why this gave strong evidence for parity violation in the weak interaction. [4]

   (e) Using sketches to help you, explain how the spin structure of weak interactions leads to parity violation in the above process. ^{60}Co has a spin of 5 and ^{60}Ni* has a spin of 4. [5]

8. (a) The semi-empirical mass formula (SEMF) for the mass of a nucleus of atomic number Z and mass number A can be written as :

$$M(Z,A) = Zm_p + (A-Z)m_n - a_v A + a_s A^{\frac{2}{3}} + a_c Z^2 A^{-\frac{1}{3}} + a_a \left(Z - \frac{A}{2}\right)^2 A^{-1} \pm \delta a_p f(A)$$

With: $a_v = 15.67; a_s = 17.23; a_c = 0.714; a_a = 93.15; a_p = 11.1$ (all in MeV/c^2).
Using the SEMF, find the atomic number Z of the most stable nucleus of mass number A=41. You can neglect the neutron-proton mass difference: $m_p \approx m_n$. [8]

(b) Estimate by how much the diameter of a nucleus changes if its mass number A is increased by a factor of 8. [2]

(c) Consider the simple two flavour neutrino mixing model. The probability of a neutrino with energy E of flavour α oscillating over a distance L into a neutrino of flavour β is given by:

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2/[eV^2]L/[\text{km}]}{E/[\text{GeV}]}\right)$$

An initially pure $\bar{\nu_e}$ beam consisting of 10^8 electron anti-neutrinos of energy $E = 2$ GeV is measured at a distance $L = 700$ km and after correcting for detector effects is found to contain 10^5 muon anti-neutrinos $\bar{\nu_\mu}$. Scanning points at several distances, points of maximum oscillation are found. The maximum number of muon anti-neutrinos $\bar{\nu_\mu}$ appearing in this beam at these maxima is found to be 8.46×10^7.

i. Estimate $\sin^2(2\theta)$. [2]

ii. What is the survival probability of electron anti-neutrinos of energy $E = 2$ GeV, at a distance $L = 2500$ km? [6]

(d) In dedicated neutrino experiments, neutrinos are often recorded using a charged current reaction with the nucleus. What is the minimum neutrino energy required for the reaction $\nu_\mu + n \to \mu^- + p$ to occur on a neutron initially at rest? You can neglect the neutrino mass and neutron-proton mass difference: $m_p \approx m_n$. [6]

(e) How can electron neutrinos ν_e and muon neutrinos ν_μ be distinguished in an experiment? [2]

(f) How can the presence of neutrinos be inferred in a typical collider experiment? [2]

(g) The decay products of a particle contain neutrinos. Is this decay a strong, weak or electromagnetic process? [2]

[Part marks]

9. (a) A quarter of an unknown radioactive substance has decayed after a day, what is the half-life of this substance in seconds? [5]

(b) Sketch or state the shell configuration of the nuclear ground state of Lithium $^{6}_{3}$Li. What can you say about Parity and Spin of this state? [5] [2]

(c) Consider the Fermi gas model of the nucleus. Is the potential well for protons

- deeper
- the same
- less deep

than that for neutrons? What is the reason for this?

(d) Which of the following reactions: [14]

i. $\mu^+ + e^- \rightarrow e^+ + \mu^-$

ii. $e^+ + \mu^- \rightarrow e^+ + \mu^-$

iii. $\Lambda^0 + \pi^+ \rightarrow p + \bar{K}^0$

iv. $\pi^+ + \pi^- \rightarrow \nu_e + \bar{\nu_e}$

v. $\mu^- \rightarrow \nu_\mu + \bar{\nu_\tau} + \tau^-$

are allowed for free particles and which are forbidden? Explain why in each case and draw one lowest order Feynman diagram for each of the allowed reactions. (Note: $\pi^+ = u\bar{d}$; $\Lambda^0 = uds$; $\bar{K}^0 = s\bar{d}$)

(e) The mean lifetime of tau leptons is $\tau_\tau = 291 \times 10^{-15}$ s and the tau mass $m_\tau = 1780$ MeV/c^2 . A tau lepton is created with a momentum of $p = 18$ GeV/c. How far does this tau lepton fly on average, before it decays? [4]

10. (a) i. What is the dominant decay channel of the Higgs boson? [1]

ii. Which decay channels contributed to the initial discovery of the Higgs boson? [2]

iii. Draw and label a leading order Feynman diagram for Higgs production via gluon–gluon fusion where the Higgs decays to a $\tau^+\tau^-$ pair and where each τ decays to an electron or positron and neutrinos. All particles, including particles in loops and neutrino types, should be labelled. [8]

iv. The coupling of the Higgs boson to a fermion anti-fermion pair is proportional to the mass of the fermion. Calculate the ratio of the branching fraction of the Higgs to decay to leptons to the branching fraction of the Higgs to decay to quarks. You may neglect any higher order corrections and phase space effects. [7]

v. Why is it more difficult to discover a Higgs decaying to a $\tau^+\tau^-$ pair than a Higgs decaying to two $\mu^+\mu^-$ pairs via the decay of two Z bosons in an LHC detector, despite the fact that the branching fraction is higher for the $\tau^+\tau^-$ decay? [3]

(b) i. Explain the process of nuclear fission. [3]

ii. Explain the process of spontaneous nuclear fission, indicating which terms from the semi-empiric mass formula (SEMF, given below) play an important role and why. [6]

$$M(Z,A) = Zm_p + (A-Z)m_n - a_v A + a_s A^{\frac{2}{3}} + a_c Z^2 A^{-\frac{1}{3}} + a_a \left(Z - \frac{A}{2}\right)^2 A^{-1} \pm \delta a_p f(A)$$