UNIVERSITY OF CAMBRIDGE

NATURAL SCIENCES TRIPOS Part II

May–June 2020 **1 hour 15 minutes**

PHYSICS (6)
PHYSICAL SCIENCES: HALF SUBJECT PHYSICS (6)

PARTICLE AND NUCLEAR PHYSICS

Candidates offering this paper should attempt a total of ***four*** *questions:* ***three*** *questions from Section A and* ***one*** *question from Section B.*

The approximate number of marks allocated to each question or part of a question is indicated in the right margin. This paper contains ***four*** *sides, including this coversheet. You may use the formula handbook for values of constants and mathematical formulae, which you may quote without proof.*

You have 75 minutes (plus any pre-agreed individual adjustment) to answer this paper. Do not start to read the questions on the subsequent pages of this question paper until the start of the time period.

Please treat this as a closed-book exam and write your answers within the time period. Downloading and uploading times should not be included in the allocated exam time. If you wish to print out the paper, do so in advance. You can pause your work on the exam in case of an external distraction, or delay uploading your work in case of technical problems.

Section A and the chosen section B question should be uploaded as separate pdfs. Please name the files 1234X_Qi.pdf, where 1234X is your examination code and i is the number of the question/section (A or 4 or 5).

STATIONERY REQUIREMENTS	SPECIAL REQUIREMENTS
Master coversheet	Mathematical Formulae handbook
	Approved calculator allowed

SECTION A

*Attempt **all** questions in this Section. Answers should be concise and relevant formulae may be assumed without proof.*

1 Estimate the cross-section ratio

$$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

for the electromagnetic interaction at total centre-of-mass energies of $5, 15$ and 360 GeV. Why do you expect R to be inaccurate at 360 GeV? [4]

2 By considering the lowest-order Feynman diagrams, show whether charged or neutral current interactions or both can contribute to the following processes:

(a) $\nu_X + d \to u + e^-$,

(b) $\nu_X + d \to d + \nu_X$, and

(c) $\nu_X + e^- \to \nu_X + e^-$,

where ν_X is any of ν_e, ν_μ or ν_τ. [4]

3 The total interaction cross-section for neutrons incident upon natural indium (96% ${}^{115}_{49}\text{In}$) is $\sim 5 \times 10^4$ barns and peaks at a neutron kinetic energy of 1.46 eV, corresponding to the formation of a compound nucleus of spin $J = 5$. Given that the spin of ${}^{115}_{49}\text{In}$ is $J = 9/2$, estimate the probability of a neutron being emitted in the decay of this compound nucleus. [4]

[*You may wish to use the Breit-Wigner resonance formula*

$$\sigma_{x+X\to y+Y} = \frac{g\pi\lambda\!\!\!^{-2}\Gamma_x\Gamma_y}{(E-E_0)^2 + \Gamma^2/4}\ .$$

The mass of a neutron is 1.68×10^{-27} *kg.*]

SECTION B

Attempt one question from this section

4 (a) Explain the meaning of the terms Grand Unified Theories and baryon-number violation. [3]

(b) Grand Unified Theories predict that protons can decay through the annihilation of two valence quarks to create a lepton and antiquark via the exchange of a very heavy intermediate boson. Sketch two possible Feynman diagrams for this decay of a proton, indicating the final-state particles. Explain why these Feynman diagrams are non-Standard-Model diagrams. [4]

(c) Assuming the proton decay process is dominated by the boson propagator, show that the partial width for proton decay has the form

$$\mathit{\Gamma} = \frac{\alpha_{\mathrm{G}}^2 m_{\mathrm{p}}^5}{m_X^4},$$

where α_{G} is the relevant coupling constant, m_{p} is the proton mass and m_X is the heavy boson mass. [4]

(d) Estimate the lifetime of the proton for a propagator mass, $m_X = 2 \times 10^{14}$ GeV. Give your answer in seconds. [3]

(e) Describe an experiment that could be used to search for proton decay, explaining your reasoning. [5]

[*You may assume* $\alpha_{\mathrm{G}} = 0.024$ *and* $m_{\mathrm{p}} = 938\,\mathrm{MeV}/c^2$.]

(TURN OVER

5 (a) Outline the evidence in favour of the Shell Model of atomic nuclei. [5]

According to a particular Shell-Model calculation, using a square-well potential with rounded edges and a strong spin-orbit interaction, the nuclear levels, in increasing order of energy, are

$$1s_{1/2},\ 1p_{3/2},\ 1p_{1/2},\ 1d_{5/2},\ 2s_{1/2},\ 1d_{3/2},\ 1f_{7/2},\ 2p_{3/2},\ \cdots\cdots$$

(b) Show that the model predicts $\frac{5}{2}^+$ for the ground-state spin and parity of ${}^{17}_{9}\mathrm{F}$. What does it predict for the spins and parities of the ground states of ${}^{14}_{7}\mathrm{N}$, ${}^{30}_{14}\mathrm{Si}$ and ${}^{39}_{16}\mathrm{S}$? [6]

(c) A study was made of the electromagnetic decays of three excited states of ${}^{17}_{9}\mathrm{F}$, each with an excitation energy of less than 5 MeV. The γ-radiations emitted were found to be

(i) E1 radiation at 2.1, 3.7 and 4.6 MeV,

(ii) M1 radiation at 1.6 MeV,

(iii) E2 radiation at 0.9 and 1.6 MeV, and

(iv) faint radiation of unidentified type at 3.0 MeV.

Explaining your reasoning carefully, establish a level scheme for ${}^{17}_{9}\mathrm{F}$ compatible with these data. Draw the scheme, labelling the levels with their energies, spins and parities. State the likely nature of the 3.0 MeV radiation and indicate the extent to which other schemes could easily fit the data. [8]

END OF PAPER