
EXAMINATION PAPER 2012-2013

NUCLEI AND PARTICLES

Duration: 120 MINS

This paper contains 9 questions.

Answer **all** questions in **Section A** and **one** question in **each** of **Section B** and **Section C**.

Each section carries 1/3 of the total marks for the exam paper and you should aim to spend about 40 mins on each.

A Sheet of Physical Constants is provided with this examination paper.

Only university approved calculators may be used.

A foreign language translation dictionary (paper version) is permitted provided it contains no notes, additions or annotations.

Section A

A1. What is meant by "Magic Numbers"? Give three pieces of experimental evidence for the existence of Magic Numbers. [4]

A2. For a nuclide P with atomic number, Z^P and atomic mass number A^P, write down the relation between nuclear mass, the proton mass, the neutron mass, and the binding energy, B_P^E. In case of α-decay $P \to D + \alpha$, derive the relation between the Q-value of the energy released and the binding energy of the parent particle, B_P^E, the binding energy of the daughter particle, B_D^E, and the binding energy of the α-particle, B_α^E. [4]

A3. The deuteron is a bound state of a proton and a neutron. There are no bound states of two protons or two neutrons. Use this information and the symmetry properties of the deuteron wavefunction to deduce the spin of the deuteron in its ground-state. [4]

A4. The production cross section of the Higgs boson (H) in the gluon-gluon fusion process at the Large Hadron Collider is $\sigma_{gg\to H} = 20$ pb for the Higgs boson with mass 125 GeV. The decay branching ratio of the Higgs boson into two photons is $Br(H \to \gamma\gamma) = 2 \times 10^{-3}$. What is the total integrated luminosity that is required to measure the cross section of $gg \to H \to \gamma\gamma$ process with an accuracy 10%? For simplicity you can neglect background processes. [5]

A5. Consider the Shell Model. Given that the first two shells are 1s,1p and 1d shells, determine spin and parities of the following nuclei in their ground state: ${}^{15}_{8}$O, ${}^{7}_{4}$Be, ${}^{6}_{3}$Li. In case where there are several possible states, list all possibilities. [3]

Section B

B1. a) What is meant by “form-factor”? How does the differential cross-section for scattering of nuclei depend on the form factor? [2]

b) Explain qualitatively why the scattering cross-section for scattering of sufficiently high energy electrons off a nucleus displays diffraction maxima and minima, and how this diffraction pattern can be used to obtain information about the charge distribution in the nucleus. [5]

c) Electrons of energy 1 GeV are scattered off the nuclei, ^{64}Cu, ^{108}Ag and ^{197}Au. The first diffraction minima are observed at scattering angles 7.4^0, 6.2^0 and 5.0^0 for the three nuclei respectively. Write down the relation between the momentum transferred in the scattering process and the scattering angle. Hence make an estimate of the radii of the three nuclei and comment on the dependence of the radii on the atomic mass numbers. [11]

d) What is the additional information on nuclei that can be obtained from scattering processes using neutrons rather than electrons? [2]

TURN OVER

B2. a) Discuss qualitatively how the shape of a nucleus changes during nuclear fission. [2]

b) Hence explain why spontaneous fission is extremely rare, but fission can be induced by bombarding fissile material with neutrons. [4]

c) Explain why fission can be induced by low-energy (cold) neutrons for ${}^{235}_{92}\mathrm{U}$, whereas neutrons must have a kinetic energy above 1 MeV in order to induce fission in ${}^{238}_{92}\mathrm{U}$ [4]

d) Why is nuclear fission usually followed by β-decay? [3]

e) Explain how a chain reaction occurs in nuclear fission. [3]

f) Why is it necessary for a sample of fissile material to be greater than a critical mass in order for a chain reaction to occur? [2]

g) In a nuclear reactor how is the chain reaction controlled in order to produce a steady output of energy? [2]

Section C

C1. a) Draw the Feynman Diagrams for the annihilation process $e^+e^- \rightarrow \mathrm{W}^+\,\mathrm{W}^-$. [2]

b) Find the minimal value of the energy E of an e^+ scattering off an e^- with energy $E/2$ (i.e. half of the e^+ energy) that is required in order to produce a W^+W^- pair ($M_W = 80$GeV/c^2). For simplicity, you may neglect the mass of the electron as compared to its energy. [8]

c) Write down electric charges of all fundamental fermions. [4]

d) Calculate

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

for center-of-mass energy just below the threshold for “charm” production and for center-of-mass energy just below the threshold for b-quark production. Explain your results. Contribution from weak interactions can be ignored. [5]

Explain how the experimentally measured value of R can be used as evidence for the existence of quark colours. [1]

TURN OVER

C2. (a) K-mesons and π-mesons have negative parity and zero intrinsic spin. ρ-mesons have negative parity and intrinsic spin one.

Explain why the observation of the weak-interaction decay

$$K^+ \rightarrow \pi^+ + \pi^0$$

provides evidence that weak interactions violate parity, and why the decay

$$\rho^+ \rightarrow \pi^+ + \pi^0$$

can proceed via the strong interaction. [3]

(b) Draw the relevant Feynman graphs for the semi-leptonic decay of the K^0 (quark content $\bar{s}d$): $K^0 \rightarrow \pi^- + \mu^+ + \nu_\mu$

and the semi-leptonic decay of $\overline{K}^0$: $\overline{K}^0 \rightarrow \pi^+ + \mu^- + \overline{\nu}_\mu$ [4]

(c) What is meant by CP? [2]

(d) Show that superposition

$$|K_L\rangle = \frac{1}{\sqrt{2}} \left(|K^0\rangle + |\overline{K}^0\rangle \right)$$

is CP-odd whereas the superposition

$$|K_S\rangle = \frac{1}{\sqrt{2}} \left(|K^0\rangle - |\overline{K}^0\rangle \right)$$

is CP-even. [2]

(e) From the fact that the weak interactions are (to a very good approximation) CP invariant, explain why $|K^0\rangle$ and $|\overline{K}^0\rangle$ are *not* mass eigenstates, whereas the superposition states $|K_L\rangle$ and $|K_S\rangle$ are. [2]

(f) Explain why K_S decays only into two pions whereas K_L can only decay into three pions. [2]

(g) The mean lifetime of K_S, τ_S, is much shorter than the mean lifetime of K_L. A K_0 is produced at time $t = 0$ then, after a time t, which is much larger than τ_S, it decays semi-leptonically. Explain why in such a case the decay $K_0 \to \pi^+\mu^-\overline{\nu}_\mu$ is just as likely as $K_0 \to \pi^-\mu^+\nu_\mu$. [5]

END OF PAPER