UNIVERSITY OF SOUTHAMPTON PHYS3002W1

SEMESTER 2 EXAMINATION 2013-2014

NUCLEI AND PARTICLES

Duration: 120 MINS (2 hours)

This paper contains 9 questions.

Answers to Section A must be in separate answer books from Section B and Section C

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.

An outline marking scheme is shown in brackets to the right of each question.

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. Consider the Shell Model. Determine the spin and parity of ${}^{13}_{6}$C and ${}^{10}_{5}$B. Explain your results by determining the number of protons and neutrons and demonstrating how they fill nuclear shells. [4]

A2. The specific activity of the C^{14} nuclide in a wooden relic is measured to be κ ($\kappa < 1$) as compared to that in recently felled trees. The half-life of the C^{14} nuclide is $T_{1/2}$. Determine the age T_0 of the wooden relic. [3]

A3. Sketch the curve of the binding energy per nucleon $B(Z,A)/A$ against A for stable nuclei over the entire range of A. Calculate $B(Z,A)/A$ for the nuclide ${}^{12}_{6}$C [The atomic mass of ${}^{12}_{6}$C is defined to be exactly equal to 12 u, where u= 931.49 MeV/c^2]. [4]

A4. Explain how the energy spectrum of electrons produced in β-decay processes is evidence for the existence of the neutrino. State the main properties ascribed to the neutrino. Calculate the Q-value for neutron β-decay. [4]

A5. Calculate the total energy in MeV and momentum in MeV/c of an electron with a kinetic energy of 20 MeV. What is its de Broglie wavelength in fm? [5]

Section B

B1. (a) According to the liquid drop model the nuclear binding energy may be approximated by the semi-empirical formula

$$B(A,Z) = a_V A - a_S A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_A \frac{(Z-N)^2}{A} + \frac{\left((-1)^Z + (-1)^N\right)}{2} \frac{a_P}{A^{1/2}}$$

where A is the atomic mass number, Z is the atomic number and $N = A - Z$. From fitting to the measured nuclear binding energies, the values of the parameters are $a_V = 15.56$ MeV, $a_S = 17.23$ MeV, $a_C = 0.697$ MeV, $a_A = 23.285$ MeV, $a_P = 12.0$ MeV.

Discuss the physical origin of each of the terms on the right-hand side of the above formula. [5]

(b) Considering a set of isobaric nuclei, show that the relationship between A and Z takes the form

$$Z = A/(2 + \frac{a_c}{2a_A} A^{2/3})$$

in the liquid drop model for naturally occurring nuclei with odd atomic mass number. [5]

(c) State the assumptions of the Shell Model. Explain how the spacing of the nuclear energy levels $1s_{1/2}$, $1p_{3/2}$, $1p_{1/2}$, $1d_{5/2}$, $2s_{1/2}$, $1d_{3/2}$, $1f_{7/2}$ gives rise to the first four magic numbers. [5]

(d) A stationary ^{200}Pb nucleus emits an alpha-particle with kinetic energy $T_\alpha = 5.77$ MeV. Find the recoil velocity of the daughter nucleus. [3]

What fraction of the total energy liberated in this decay is accounted for by the recoil energy of the daughter nucleus? [2]

TURN OVER

B2. (a) List the main physical assumptions that Rutherford made in order to derive the classical differential cross-section formula describing the scattering of α-particles from a thin metal foil target. [6]

(b) State the reasons for the observed deviations from Rutherford scattering for D $<$ 10 fm. [2]

(c) What are the advantages of using electron beams instead of α-particles? Give the definitions of the momentum transfer $\mathbf{q}$ and the form-factor $F(\mathbf{q})$. Explain how the form-factor modifies the point-like Mott cross-section for electron scattering. [4]

(d) Write down the equation relating the form-factor $F(\mathbf{q})$ to the charge density $\rho(r)$. Evaluate $F(\mathbf{q})$ for each of the following cases: (i) zero momentum transfer $\mathbf{q} = 0$, (ii) when the entire charge of the nucleus is concentrated into a point at the origin. [6]

(e) Is there any advantage in using (i) neutron beams, (ii) proton beams, in place of the α-particles? [2]

Section C

C1. (a) What are carriers of the weak interactions and what are their quantum numbers and properties? List all elementary particles involved in weak interactions. [3]

(b) Draw all Feynman diagrams representing vertices (interactions) for particles involved in the weak interactions. [3]

(c) Using these vertices, draw the Feynman diagram for Z-boson pair production in quark-antiquark collisions to lowest order in perturbation theory. [2]

(d) The minimal centre-of-mass energy (CME) for the reaction $e^+e^- \to ZZ$ at LEP linear collider is $\sqrt{s} = 2M_Z \times c^2$. In the case of stationary positrons, what is the energy of the electron that would be required to achieve this CME? [5]

(e) By making a diagram or table, show how a left-handed electron e_L^- transforms under (i) a parity transformation P, (ii) a charge conjugation transformation C, (iii) the combinations of CP (or PC). Repeat this for a left-handed neutrino ν_{eL}, and indicate which of the resulting neutrino states are produced in weak interactions, and which are not. [6]

(f) Under which transformation(s) from those listed in part (e) are weak interactions (almost) conserved? [1]

TURN OVER

C2. (a) What are carriers of the strong interactions and what are their quantum numbers and properties? [2]

(b) Draw all Feynman diagrams representing vertices (interactions) for particles involved in strong interactions. [3]

(c) Which quantity(quantities) is (are) conserved in the strong interactions? [2]

(d) The Ω^- baryon has strangeness S = -3. What is its quark content? [1]

(e) Discuss why it was necessary to introduce "colour" into the quark model. Use the concept of colour to explain why the spin of the Ω^- must be $\frac{3}{2}$. [4]

(f) Ω^- can be produced in $\pi^+ p$ scattering (via the strong interactions) together with three other identical particles. Explain why these particles must be K^+. [3]

(g) What is the minimum energy of a π^+ that can scatter off a fixed proton target to produce an Ω^-? [$m_{\Omega^-} = 1672$ MeV/c^2, $m_{\pi^\pm} = 140$ MeV/c^2, $m_{K^+} = 494$ MeV/c^2]. [5]

END OF PAPER

