QUEEN'S UNIVERSITY BELFAST

PHY2005
Exam Time Table
Code PHY2005

Use lined, single-sided A4 paper
with a black or blue pen.
Write your student number
at the top of every page.

Any non-graphical calculator, except those with pre-programmable memory, may be used in this examination

LEVEL 2
Examination contributing to the Degrees of Bachelor of Science (BSc) and Master in Science (MSci)

PHY2005 - EXAM
Atomic and Nuclear Physics
Monday, 10th August 2020, 09.30 - 13.30

Examiners: Prof S Matthews, Dr P van der Burgt
and the Internal Examiners
Dr J Greenwood (j.greenwood@qub.ac.uk)

Answer ALL TEN questions in Section A for 4 marks each.
Answer ONE question in Section B for 30 marks.
Answer ONE question in Section C for 30 marks.
You have FOUR hours to complete and upload this paper.

Contact the module coordinator if you have queries/problems at s.sim@qub.ac.uk and copy to mpts@qub.ac.uk

By submitting the work, you are declaring that:

1. The submission is your own original work and no part of it has been submitted for any other assignments;
2. You understand that collusion and plagiarism in an exam are major academic offences, for which a range of penalties may be imposed, as outlined in the Procedures for Dealing with Academic Offences.

QUEEN'S UNIVERSITY BELFAST
SCHOOL OF MATHEMATICS AND PHYSICS

PHYSICAL CONSTANTS

Speed of light in a vacuum	$c = 3.00 \times 10^{8}\ \text{ms}^{-1}$
Permeability of a vacuum	$\mu_0 = 4\pi \times 10^{-7}\ \text{Hm}^{-1}$ $\approx 1.26 \times 10^{-6}\ \text{Hm}^{-1}$
Permittivity of a vacuum	$\varepsilon_0 = 8.85 \times 10^{-12}\ \text{Fm}^{-1}$
Elementary charge	$e = 1.60 \times 10^{-19}\ \text{C}$
Electron charge	$= -1.60 \times 10^{-19}\ \text{C}$
Planck Constant	$h = 6.63 \times 10^{-34}\ \text{Js}$
Reduced Planck Constant	$\hbar = 1.05 \times 10^{-34}\ \text{Js}$
Rydberg Constant for hydrogen	$R_\infty = 1.097 \times 10^{7}\ \text{m}^{-1}$
Unified atomic mass unit	$1\text{u} = 1.66\text{x}10^{-27}\ \text{kg}$ $1\text{u} = 931\ \text{MeV/c}^2$
1 electron volt (eV)	$= 1.60 \times 10^{-19}\ \text{J}$
Mass of electron	$m_e = 9.11 \times 10^{-31}\ \text{kg}$
Mass of proton	$m_p = 1.67 \times 10^{-27}\ \text{kg}$
Mass of neutron	$m_n = 1.67 \times 10^{-27}\ \text{kg}$
Molar gas constant	$R = 8.31\ \text{JK}^{-1}\text{mol}^{-1}$
Boltzmann constant	$k = 1.38 \times 10^{-23}\ \text{JK}^{-1}$
Avogadro constant	$N_A = 6.02 \times 10^{23}\ \text{mol}^{-1}$
Gravitational constant	$G = 6.67 \times 10^{-11}\ \text{Nm}^2\text{kg}^{-2}$
Acceleration of free fall on the Earth's surface	$g = 9.81\ \text{ms}^{-2}$

SECTION A

Answer ALL 10 questions in this section

Full explanations of your answers are required to attain full marks

1 The state of a single-electron atom can be identified by the quantum numbers n, l, j and m_j. List all the allowed combinations of l, j and m_j if $n = 3$. **[4]**

2 Consider atomic states with total orbital angular momentum quantum number $L = 1$ and total spin quantum number $S = 3/2$. Give all the allowed values for J, the total angular momentum quantum number, and calculate the total number of distinct angular momentum states for this case. **[4]**

3 (a) Aluminium has atomic number $Z = 13$. Apply the Aufbau principle to deduce the *electron configuration* for the ground state of neutral aluminium.

(b) Deduce the spectroscopic term for the ground state of neutral aluminium. **[4]**

4 Briefly explain the nature of the spin-orbit interaction and how this gives rise to fine-structure in atomic spectra. **[4]**

5 For each of the following transitions, indicate if the transition is allowed. If not allowed briefly explain why.

(a) $5f\ ^2F_{7/2} \rightarrow 3d\ ^2D_{5/2}$

(b) $1s^2\ 2s^2\ 2p^3\ ^2D_{5/2} \rightarrow 1s^2\ 2s^2\ 2p^3\ ^4S_{3/2}$

(c) $1s^2\ 2s\ 2p^5\ ^3P_1 \rightarrow 1s^2\ 2s^2\ 2p^4\ ^3P_2$

[4]

6 It is believed that the inter-nucleon force is repulsive at short range and is mediated by ρ and ω *mesons*. If their range is about 0.5 fm then estimate the mass energy in MeV of these particles, stating your method. **[4]**

7 Estimate the mass density for the central part of a nucleus of ^{174}Hf. State any approximations or assumptions. **[4]**

continued …

SECTION A

8 Briefly describe the Lawson criterion for fusion plasmas. At what range of temperatures do we need to maintain the plasma for efficient fusion?

[4]

9 ^{64}Cu can decay via β^+ emission with an end-point kinetic energy of 0.653 MeV. By considering the positron as a point particle, show that we do not expect angular momentum to be transferred to the nucleus in this decay. **[4]**

10 Briefly describe the process of internal conversion in nuclear decay. **[4]**

[END OF SECTION A]

continued …

SECTION B

Answer <u>ONE</u> question from this section

11(a) Summarize the postulates of the Bohr model for single-electron atoms. **[4]**

(b) (i) Write down a Bohr-model formula for the energy of an electron in a single-electron atom if the principal quantum number is n, the nuclear charge is $+Ze$, and the reduced mass is μ. **[3]**

(ii) Use the Bohr model to calculate the difference in wavelength of photons emitted by hydrogen in the transition between $n = 3$ and $n = 2$ and those emitted by tritium in the same transition. **[6]**

[Tritium nuclei contain one proton and two neutrons.]

(c) The energy-level diagram (**see next page**) shows the lowest eight energy levels of singly-ionized calcium (Ca^+). Vertical lines indicate permitted transitions between levels. The ground state has electron configuration $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s$ and spectroscopic term $^2S_{1/2}$, as indicated in the diagram (note: filled inner electron shells are omitted from the configuration label in the diagram). All the excited states shown have the same filled inner electron shells as the ground state. However, the orbital occupied by the outermost electron varies between the states.

(i) Level-3 and Level-4 have the same electron configuration; they differ only in the J quantum number. By considering rules for permitted transitions and the expected energy ordering of electron orbitals, deduce the configuration and term for Level-3 and Level-4, giving clear reasons for your answers. **[5]**

(ii) Following from your identifications in (b)(i), give configurations and terms for each of the other excited energy levels in the figures. Level-1 and Level-2 share a configuration, as do Level-6 and Level-7. **[7]**

(iii) According to the Bohr model, the energy of an electron orbital depends only on the principal quantum number, n. Explain, in physical terms, why the energies of these states in Ca^+ are significantly affected by the orbital angular momentum quantum number, l, of the outer occupied orbital too. **[5]**

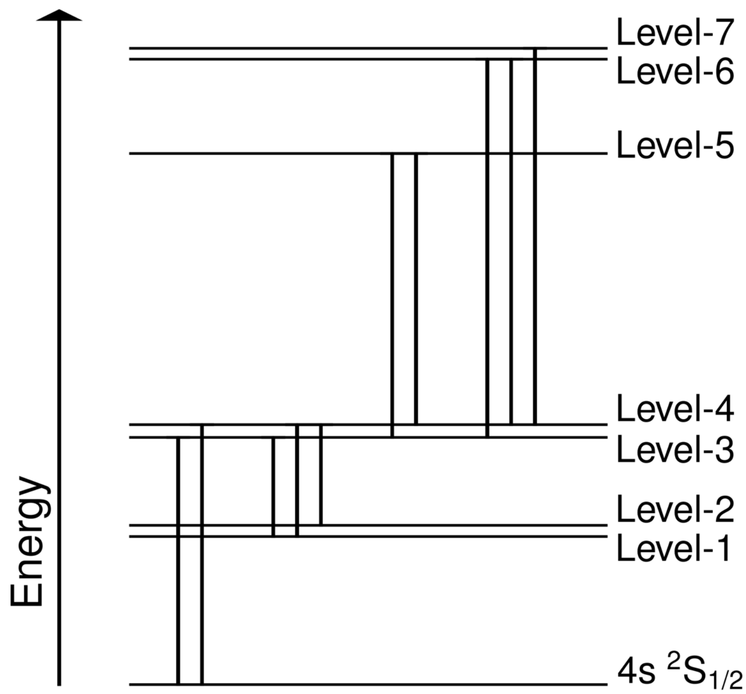
[Calcium has atomic number $Z = 20$.]

[Q11: continued with diagram on next page]

continued …

SECTION B

[Q11 continued: diagram for part (c) from previous page]



continued …

SECTION B

12(a) (i) Give the allowed values for the total spin quantum number, S, for a two-electron atom. **[2]**

(ii) Explain why the ground state of a two-electron atom has term $^1S_0$. **[4]**

(b) (i) Find all the possible configurations and terms for states of the helium atom in which one electron occupies an orbital with $n = 1$ and the other occupies an orbital with $n = 2$. Carefully explain all steps in your approach. **[6]**

(ii) Draw an energy-level diagram for helium in which you show the ground state and all of the excited states you obtained in (b)(i). You do not need to show the energy gaps between the states to scale but your diagram should clearly indicate the energy ordering of the states. You do not need to consider fine-structure effects. **[6]**

(ii) Explain in detail the physics underlying the energy ordering of the states in your diagram from part (b)(ii). **[12]**

[END OF SECTION B]

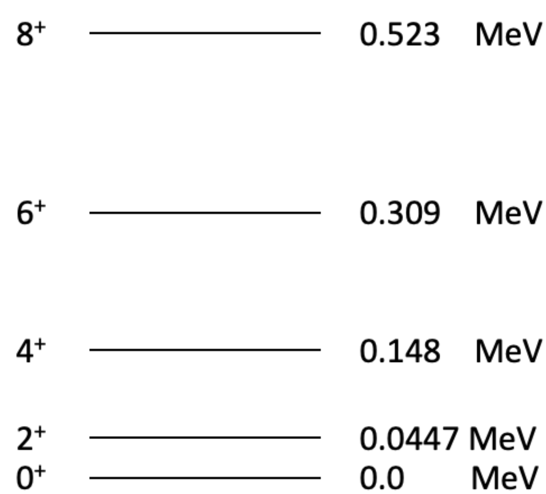
continued …

SECTION C

Answer ONE question from this section

13(a) Briefly describe three pieces of evidence for the existence of so-called *magic numbers* of protons and neutrons in nuclei. **[6]**

(b) The energy-level diagram below is for the lower lying rotational levels of ^{238}U. State with reasons how they are identifiable as rotational rather than vibrational states. Using the 8^+ level, make an estimate of the nuclear moment of inertia in kg m^2. Describe, briefly, with a sketch, the phenomenon of *back bending*. **[10]**



(c) With the aid of one or more sketches, describe, in outline, the process of nuclear fission. Include a discussion of what fission products are produced, the energy released and how neutron capture can induce fission. **[14]**

continued …

SECTION C

14(a) Explain, with the use of a figure, how beams of heavy ions, such as protons, can give advantages over the use of X-rays in the treatment of cancers. **[7]**

(b) Nuclear fuel can be stored in water. Fission reactions are accompanied by β decay causing the appearance of Cerenkov emission. With the aid of a sketch, derive the conditions for Cerenkov radiation and thus the minimum kinetic energy for it to be produced by electrons in water. If a beam of protons with 800 MeV of kinetic energy were to be stopped in water, up to what angle away from the initial direction would we expect Cerenkov radiation to be present? Show your working and state any assumptions. **[12]**

(c) Briefly describe the three main mechanisms by which gamma rays interact with a solid. In doing so, give an indication of which of these would be dominant in a heavy element such as Pb at gamma ray energies of 0.1 MeV, 1 MeV and 10 MeV and briefly state why. **[11]**

END OF EXAMINATION