QUEEN'S UNIVERSITY BELFAST

PHY2005

Exam Time Table Code PHY2005

Any calculator, except one with pre-programmable memory, may be used in this examination.

Answer Books A, B and C.

LEVEL 2
EXAMINATION CONTRIBUTING TO THE DEGREES OF BACHELOR OF SCIENCE (BSc) AND MASTER IN SCIENCE (MSci)

PHY2005
Atomica and Nuclear Physics

Duration: 3 Hours

Wednesday, 25th April 2018 9:30 AM - 12:30 PM

Examiners: Prof. P. Browning
Dr. P. van der Burgt
and the Internal Examiners

Answer ALL TEN questions in Section A.
Answer ONE question from Section B AND answer ONE question from Section C.
Section A questions are worth 4 marks each.
Section B and Section C questions are worth 30 marks each.

Use a separate answer book for each Section.
Follow the instructions on the front of the answer book. Enter your Anonymous Code number and Seat number, but NOT your name.

QUEEN'S UNIVERSITY BELFAST
SCHOOL OF MATHEMATICS AND PHYSICS

PHYSICAL CONSTANTS

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

SECTION A

Use a section A answer book

Answer ALL 10 questions in this section

Full explanations of your answers are required to attain full marks

1 State the postulates of the Bohr model of the hydrogen atom. **[4]**

2 Consider atomic states with orbital angular momentum quantum number $L = 2$ and spin quantum number $S = 3/2$.

(a) Give the allowed values of the total angular momentum quantum number, J, for this case.

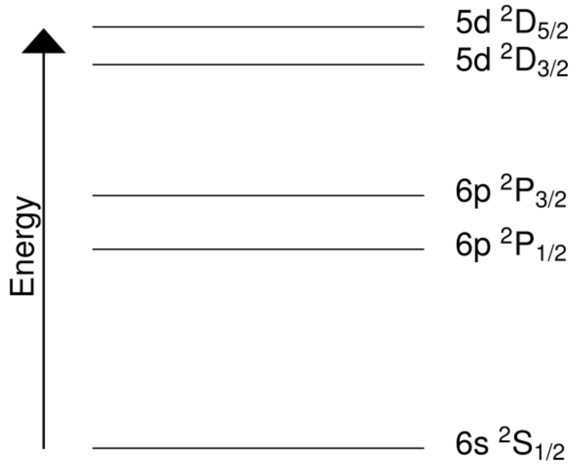
(b) Calculate the total number of distinct angular momentum states for this case.

[4]

3 Give the electron *configuration* of the ground state of the helium atom in spectroscopic notation. Explain why the *term* for this state is $^1S_0$. **[4]**

4 Use the Aufbau principle to determine the ground-state electron configuration of nickel (atomic number, $Z = 28$). **[4]**

5 The figure below shows the first few energy levels of the Cs atom (atomic number, $Z = 55$). The spectroscopic terms and outer shell configurations are indicated in the figure (filled inner shells are not listed). Make a copy of this figure and mark on it all permitted radiative transitions between these levels. **[4]**



6 Assuming that the inter-nucleon potential is mediated by exchange of π-*mesons*, use the uncertainty principle along with assumptions about the range and velocity of the *mesons* to estimate their mass.

[4]

7 Explain briefly why, at low atomic mass, the stable nuclei tend to have similar proton and neutron numbers, i.e. N ~ Z. Why does the stability veer away towards N > Z for high atomic mass nuclei?

[4]

8 Explain in qualitative terms, with the aid of a diagram, why the energy of α particles emitted from nuclei and the lifetime of the nuclei are closely related.

[4]

9 An atom of mass M_A, in an excited state E_i decays to a final state E_f with the emission of a γ-ray. Derive a relationship between the change in nuclear energy level and the energy of the γ–ray**.**

[4]

10 Describe, briefly, how β-decay can be used for dating rocks.

[4]

SECTION B

Use a Section B answer book

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

11(a) States of single-electron atoms can be labelled using the quantum numbers n, l, j and m_j.

(i) Give the physical meanings of l, j and m_j, and state how their allowed values are related to n and each other. **[6]**

(ii) Write down a formula that relates the energies of levels in single-electron atoms to the value of n. Hence calculate the wavelength of the transition between $n = 2$ and $n = 3$ for singly-ionized helium (i.e. He^+). **[6]**

[Helium has atomic number $Z = 2$.]

(b) With reference to the electron shell structure of multi-electron atoms, explain the concept of *electron screening* and outline how it can be used to understand the differing energies of electron orbitals in multi-electron atoms. **[6]**

(c) The table below given the energies for states belonging to particular electron configurations of the alkali atoms Na ($Z = 11$), K ($Z = 19$) and Rb ($Z = 37$). In each case, the energy is measured relative to first ionization.

(i) Calculate the effective nuclear charge for the 5p orbital in each of these three atoms. **[3]**

(ii) With reference to electron screening, account for the differences between the three values you obtained in (c)(i). **[5]**

(iii) Would the effective nuclear charge for the 5s and 5d orbitals differ from those of the 5p orbitals? Give brief physical reasons for your answers. **[4]**

Atom	**Electron configuration**	**Energy**
Na	$1s^2\ 2s^2\ 2p^6\ 5p$	-0.80 eV
K	$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 5p$	-1.28 eV
Rb	$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^2\ 4p^6\ 5p$	-2.61 eV

SECTION B

12(a) **(i)** State Hund's rules for determining the lowest energy term for an electron configuration in a multi-electron atom. **[4]**

(ii) Consider states of germanium with electron configuration

$$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^2\ 4p\ 5p$$

Give the spectroscopic term of the lowest energy state for this configuration, according to Hund's rules. **[6]**

(b) Describe the origin of the spin-orbit interaction in atomic physics and explain why the energy shift of a level due to the spin-orbit interaction depends on the quantum numbers *J*, *L* and *S* via

$$\Delta E = K\ [J(J+1) - L(L+1) - S(S+1)]$$

where K is a proportionality constant (you do <u>not</u> need to derive an expression for K).

[10]

(c) Spectroscopic measurements identify three states of the germanium atom that have closely spaced energies of 5.701, 5.806 and 5.964 eV above the ground state, respectively. Given that the energy splitting between these states is due to the spin-orbit interaction, and that the states have $L = 2$ and $S = 1$, deduce the values of *J* for **each** of the three states **and** determine the sign and value for the coefficient K for this case, giving your answer in eV. **[10]**

[Germanium has atomic number $Z = 32$.]

SECTION C

Use a Section C answer book

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

13(a) Describe the mechanisms by which γ-rays interact with matter. On the basis of this, sketch a graph of the absorption coefficient of lead as a function of photon energy and label its main features. **[10]**

(b) Describe, using an appropriate figure, the process of Cerenkov radiation production. Calculate the minimum kinetic energy for an electron to create Cerenkov radiation if it passes through a medium with refractive index of 1.55. Make the same calculation for a proton. **[12]**

(c) Describe qualitatively, two differences between the stopping of electrons and heavier ions such as protons in solid matter. State one application where the particular features of ion stopping in matter can be exploited. **[8]**

SECTION C

14(a) An electron beam accelerated to 400 MeV is scattered from unknown nuclei. The first minimum in the scattering cross-section is seen to be at a scatter angle of 48°. Calculate the size of the nuclei based on this data. **[9]**

(b) Give a brief outline explanation of why, when a heavy nucleus undergoes fission, one or more free neutrons are usually produced alongside the two daughter nuclei. **[3]**

(c) A ^{90}Y nucleus undergoes β^--decay, emitting an electron with an end point kinetic energy of 2.28 MeV.

(i) Explain briefly why the β^- particle has a spectrum of energies. **[3]**

(ii) Use the relativistic energy-momentum equation to estimate the momentum of the β^- particle. **[4]**

(iii) Calculate the expected maximum transfer of angular momentum to the nucleus and compare it to the quantum unit of angular momentum. What does this tell us about a selection rule for β^- particle decay? **[6]**

(iv) Explain, qualitatively, why α–particle emission is often followed by β^- decay of the daughter nucleus. **[5]**

END OF EXAMINATION