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
Atomic and Nuclear Physics

Duration: 3 Hours

Monday, 6th August 2018 2:30 PM - 5:30 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	$g = 9.81\ \mathrm{ms^{-2}}$

continued …

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 Calculate the wavelength of the transition between energy levels with principal quantum number $n = 3$ and $n = 1$ for doubly-ionized lithium. Lithium has atomic number $Z = 3$. Give your answer to three significant figures. **[4]**

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

3 Briefly discuss electron screening in multielectron atoms and explain what is meant by the effective nuclear charge, Z_{eff}, for an electron shell in a multielectron atom. **[4]**

4 Scandium has atomic number $Z = 21$. Determine the ground state electron configuration for this atom, giving your answer in spectroscopic notation. **[4]**

5 Use the selection rules to identify all the allowed radiative transitions from the 1s3p $^1P_1$ level of helium to lower energy levels of the helium atom. Clearly indicate the total number of such transitions and give the configuration and term for the lower level of each transition. **[4]**

6 Explain briefly why there is no bound nuclear state consisting of either two protons or two neutrons. **[4]**

7 Name three mechanisms by which gamma rays can interact with a solid. Which of these becomes dominant at high gamma ray energies? **[4]**

8 For a Rutherford scattering experiment α-particles with kinetic energy 5.5 MeV are fired at a gold foil (Z=79). Calculate the classical distance of closest approach. **[4]**

continued …

SECTION A

9 Explain, briefly, why in β decay there is a spread in the energy of the emitted electron or positron. **[4]**

10 Give two pieces of evidence for the existence of the pairing force in nuclear structure. **[4]**

continued …

SECTION B

Use a Section B answer book

Answer ONE question from this section

11 **(a)** Briefly describe the Bohr model for single-electron atoms. Discuss the successes and shortcomings of this model when used to explain real laboratory spectra of atoms and ions. **[10]**

(b) The interaction energy associated with a magnetic dipole moment $\underline{\mu}$ in a magnetic field $\underline{B}$ is given by

$$\Delta E = -\underline{\mu} \cdot \underline{B}$$

Without detailed calculation, explain how this relationship can be applied to describe

(i) fine-structure in spectra due to the spin-orbit interaction and

(ii) splitting of spectral lines via the (normal) Zeeman effect.

In both cases, carefully explain the origin of the magnetic dipole moment and magnetic field involved. **[12]**

(c) The three 5s6p $^3P_{0,1,2}$ states of the cadmium atom are known to have energies of 7.240, 7.248 and 7.270 eV (above the ground state). Use these data to make a rough estimate of the strength of the magnetic field internal to the atom. Clearly explain your reasoning. **[8]**

[The Bohr magneton is given by $\mu_B = \frac{e\hbar}{2m_e} = 9.27 \times 10^{-24}\ \mathrm{J\,T^{-1}} = 5.79 \times 10^{-5}\ \mathrm{eV\,T^{-1}}$**]**

continued …

SECTION B

12 **(a)** State Hund's rules for determining the lowest energy term for an electron configuration. **[5]**

(b) Consider the excited electron configuration of neutral germanium ($Z = 32$)

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

(i) Identify all the possible terms associated with this configuration (give your answers in spectroscopic notation). **[12]**

(ii) Apply Hund's rules to determine which term is expected to have lowest energy. **[4]**

(c) For each of the following electron configurations of neutral germanium, comment on whether the number of terms will be smaller, larger, or the same as for the example in part b (i). You do not need to identify the terms or give any quantitative calculation, but you should give a short physical explanation for your answer in each case.

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

(ii) $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^2\ 4p\ 4d$

(iii) $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^2\ 4p^2$ **[9]**

continued …

SECTION C

Use a Section C answer book

Answer ONE question from this section

13 **(a)** A ^{64}Cu nucleus undergoes both β^- decay and β^+ decay.

(i) Sketch the spectrum of energies for each case and explain any difference between them. **[4]**

(ii) Use the relativistic energy-momentum equation to estimate the momentum of the β^- particle if it is emitted with maximum kinetic energy (0.5787 MeV). **[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]**

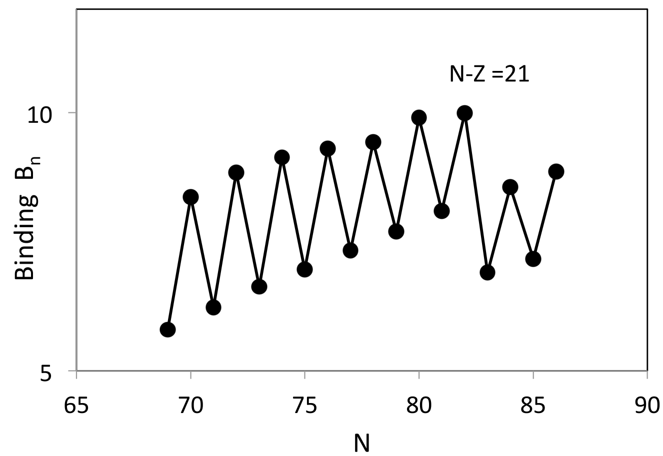
(b) **(i)** Explain in qualitative terms, with the aid of a diagram, why the energy of α particles emitted from nuclei and the lifetime of the nuclei are closely related. **[8]**

(ii) It is energetically favourable for a large nucleus to emit a carbon nucleus. Explain in qualitative terms why this is in fact rare. **[8]**

continued …

SECTION C

14 **(a)** The figure below shows how the energy to remove a final neutron from a series of isotopes varies as a function of neutron number, N, whilst keeping N-Z constant.



(i) Explain the oscillation in binding energy between odd and even neutron numbers. **[6]**

(ii) Explain the sudden drop in binding energy at N=82. **[5]**

(iii) Explain why, in the known α-decay series, the emission of α-particles is interspersed with β emission. **[5]**

(b) In the liquid drop model of the nucleus, the total binding energy can be expressed by the equation below.

$$B = a_V A - a_s A^{2/3} - a_c \frac{Z^2}{A^{1/3}} - a_{as} \frac{(A-2Z)^2}{A} - \frac{\delta(A,Z)}{A^{3/4}}$$

Explain the physics underpinning the five terms on the right hand side of the equation. **[14]**

END OF EXAMINATION