QUEEN'S UNIVERSITY BELFAST

PHY2005
Exam Time Table
Code PHY2005

Answer Books A, B and C.

Any calculator, except one 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
Atomic and Nuclear Physics

Monday, 13th May 2019 9:30 AM - 12:30 PM

Examiners: Professor P Browning
Dr P van der Burgt
and the Internal Examiners

Answer ALL TEN questions in Section A for 4 marks each.
Answer ONE question from Section B for 30 marks
and ONE question from Section C for 30 marks.

Use a separate Answer Book for each Section.
You have THREE hours to complete this paper.

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	$R_\infty = 1.097 \times 10^{7}\ \mathrm{m^{-1}}$
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	$G = 6.67 \times 10^{-11}\ \mathrm{Nm^{2}kg^{-2}}$
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 In quantum mechanics, a state of a single-electron atom can be identified by giving the quantum numbers n, l, j and m_j. Give the physical meanings l, j and m_j. **[4]**

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

3 Use the Aufbau principle to determine the ground-state electron configuration of strontium (atomic number $Z = 38$). **[4]**

4 Briefly describe what is meant by the *spin-orbit interaction* in atomic physics and comment on how its effects can be observed in atomic spectra. **[4]**

5 State whether each of the following radiative transitions is allowed. If not allowed, briefly state why.

(a) 4p $^2P_{3/2} \rightarrow$ 3s $^2S_{1/2}$

(b) 3s 4p $^3P_1 \rightarrow 2s^2$ $^3S_0$

(c) 2s $2p^4$ $^4P_{3/2} \rightarrow 2s^2$ $2p^3$ $^2D_{5/2}$ **[4]**

6 Briefly explain why, in β decay, there is a spread in the energy of the emitted electron or positron. **[4]**

7 Give a simple reason why the inter-nucleon force must be stronger than the Coulomb force and one simple reason why the inter-nucleon force must be independent of electrical charge. **[4]**

[CONTINUED]

8 α particles backscattered from a metal foil have a change in kinetic energy given by

$$\Delta K = K_0 \frac{4m/M}{(1+\frac{m}{M})^2}$$

Where m and M are the atomic mass numbers of the α particles and nuclei, respectively, and K_0 is the initial kinetic energy. For K_0= 5.5 MeV calculate the energy resolution needed to separate peaks for ^{63}Cu and ^{65}Cu in a sample foil. **[4]**

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

10 Explain the origin of the escape peaks in a gamma-ray scintillator spectrum. At which energies do they appear in the spectrum? **[4]**

[END OF SECTION A]

[CONTINUED]

SECTION B

Use a Section B answer book

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

11 **(a)** Briefly discuss the main successes and shortcomings of the Bohr model in explaining atomic spectra. **[6]**

(b) **(i)** Use the Bohr model to calculate the wavelength, λ_H, of the Balmer α transition in hydrogen. Give your answer to three significant figures. **[5]**

(ii) Explain why the wavelength of the Balmer α transition in deuterium (λ_D) will be approximately related to its value in hydrogen by

$$\frac{\lambda_D}{\lambda_H} = \frac{x + 1/2}{x + 1}$$

where $x = m_N/m_e$ is the ratio of the nucleon mass to the electron mass. **[4]**

(iii) Hence, or otherwise, calculate the shift in wavelength, $\lambda_H - \lambda_D$, for the Balmer α transition. **[3]**

[The deuterium nucleus contains one proton and one neutron.]

(c) The $1s^2\,3p \rightarrow 1s^2\,2s$ transition of the neutral lithium atom is measured to have a wavelength of 323.3 nm. Although this transition involves a change of $n = 3$ to $n = 2$ for the outer electron, the wavelength is significantly different from the Balmer α transition in hydrogen. Explain the physical reasons for this difference. **[6]**

(d) Consider each of the following three transitions. State which will have wavelength most similar to the Balmer α transition in hydrogen, and which will be most different. Justify your answers.

(i) $1s^2\,3d \rightarrow 1s^2\,2p$ transition in neutral lithium

(ii) $3p \rightarrow 2s$ transition in singly-ionized helium

(iii) $6g \rightarrow 4f$ transition in singly-ionized helium **[6]**

[Balmer α refers to the transition in single-electron atoms between the $n = 3$ and $n = 2$ levels. Lithium has atomic number $Z = 3$. Helium has atomic number $Z = 2$.]

[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) Explain what is meant by the *exchange interaction* in two-electron atoms and describe why this results in states with larger S having lower excitation energy. **[8]**

(c) **(i)** Give 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 $n = 3$. **[8]**

(ii) Which of the states from part (i) have an allowed transition to the ground state of the helium atom (give the electron configuration(s) and term(s))? **[3]**

(d) In the absence of a magnetic field, the 1s3p $^1P_1$ – 1s2s $^1S_0$ transition of the helium atom is observed as a single spectral line with wavelength of 501.568 nm. How would this transition appear if a magnetic field corresponding to $B = 1$ T were applied? **[5]**

[Helium has atomic number $Z = 2$. The Bohr magneton has value $\mu_B = 9.27 \times 10^{-24}$ J / T]

[END OF SECTION B]

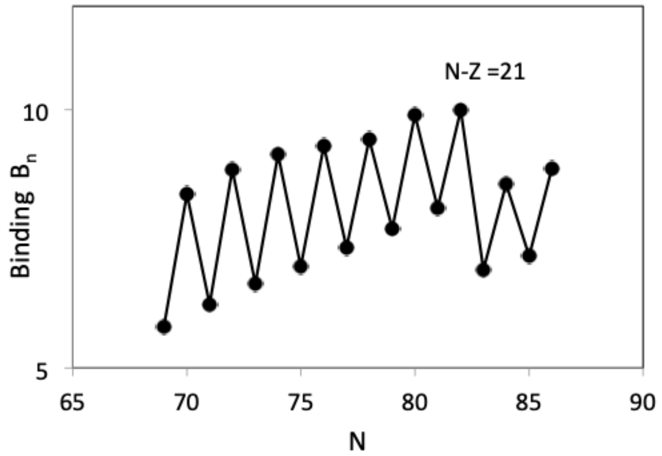
[CONTINUED]

SECTION C

Use a Section C answer book

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

13 **(a)** The figure below shows how the energy, B_N (in MeV), 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. Give one other value of N where this might be expected to happen. **[4]**

(b) It is observed that the bound state of the deuteron is $^3S_1$, whilst the $^1S_0$ state is unbound.

(i) What does this tell us about the inter-nucleon force? **[5]**

(ii) Explain, with the aid of a sketch, why the observation of an electric quadrupole moment for the deuteron implies that the inter-nucleon force has a tensor component to the spin dependence. What is the implication for the wavefunction of the deuteron? **[10]**

(iii) The deuteron is a bound *np* state. Why is there no *nn* or *pp* bound state? **[5]**

[CONTINUED]

SECTION C

14 **(a)** Give a brief explanation of why, when a heavy nucleus undergoes fission, one or more free neutrons are usually produced alongside the two daughter nuclei. **[4]**

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

(i) Use the relativistic energy-momentum equation to estimate the momentum of the β^- particle. Give the answer in both SI units and MeV/c units. **[4]**

(ii) 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^- decay? **[6]**

(iii) Explain, qualitatively, with the aid of a figure, why α–particle emission is often followed by β^- decay of the daughter nucleus. **[6]**

(c) Derive an expression for the Q value of a β^+ decay from an element, X, to an element Y. Do the same for an electron capture decay (EC). State any assumptions made. Explain why, if β^+ decay is energetically possible, then electron capture (EC) is also possible but not necessarily vice-versa. **[10]**

END OF EXAMINATION