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

Wednesday, 14th August 2019 2:30 PM - 5:30 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	$G = 6.67 \times 10^{-11}\ \mathrm{Nm^2kg^{-2}}$
Acceleration of free fall on the Earth's surface	$g = 9.81\ \mathrm{ms^{-2}}$

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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

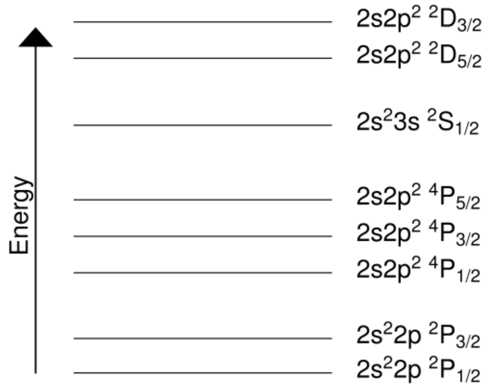
1 Give the values of the quantum numbers associated with the total angular momentum, the orbital angular momentum, and the spin for an atomic level with spectroscopic term $^2F_{5/2}$. What is the smallest value for the principal quantum number, n, for a state of the hydrogen atom that can have such a term? **[4]**

2 If the orbital angular momentum quantum number $L = 4$ and the spin quantum number $S = 1$, what are the allowed values of the total angular momentum quantum number, J? How many distinct angular momentum states exist for this case? **[4]**

3 In the Hartree theory of atomic structure, a *central field approximation* is made whereby it is assumed that the potential energy, $U(r)$, depends only on radial position, r. For a neutral atom with nuclear charge, Z, write down expressions for how $U(r)$ should behave for both $r \to 0$ and $r \to \infty$. Briefly justify both your statements. **[4]**

4 Give the ground state electron configuration for iron (atomic number $Z = 26$). **[4]**

5 The energy-level diagram below shows the first few levels of the Boron atom ($Z = 5$) with their electron configurations and terms. For simplicity, the filled inner 1s shell is not included in the configurations. Make a copy of this diagram and mark on it all the allowed radiative transitions between these levels. **[4]**



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SECTION A

6 For the isotope, ^{64}Cu, β decay can proceed by either β^+ or β^- emission. Explain, briefly, why the spectrum of the β -particles for the latter has a peak at lower kinetic energy. What is the difference, between the two cases, in the second particle emitted? **[4]**

7 Briefly describe the Lawson criterion for fusion plasmas. At what range of temperatures do we need to maintain the plasma for efficient fusion? **[4]**

8 Describe, in outline, what is meant by the Bragg peak in stopping of heavy particles, such as protons or alpha particles. Give one example of an application. **[4]**

9 For an electron of kinetic energy 0.6 MeV calculate the momentum using MeV and MeV/c units. Show your working and then give the answer in SI units as well. (The electron mass energy is 0.511MeV.) **[4]**

10 Name the three principal mechanisms by which gamma rays interact with a solid. Which one do you expect to be dominant at photon energies well above 1 MeV? **[4]**

[END OF SECTION A]

continued …

SECTION B

Use a Section B answer book

Answer ONE question from this section

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

(b) Briefly discuss the extent to which the Bohr model successfully accounts for the spectra of single-electron atoms. Your answer should include comments on both successes and shortcomings of the model in this context. **[4]**

(c) Write down a Bohr-model formula for the energy of an electron orbital with principal quantum number n. Use your expression to calculate the wavelength of the $n = 5$ to $n = 3$ transition in Be^{3+} (i.e. three-times ionized Beryllium) to three significant figures. Beryllium has atomic number $Z = 4$. **[6]**

(d) The ground state of neutral Beryllium has configuration $1s^2 2s^2$.

(i) Give the spectroscopic term for this configuration and explain your answer. **[4]**

(ii) Explain why the energies associated with the occupied 1s and 2s orbitals in the ground state of Beryllium will differ from the energies predicted for those orbitals by the formula you used in part **(c)**. Your answer should comment on the underlying physics and clearly explain whether the energies will be smaller or larger compared to the Bohr formula for both orbitals. **[8]**

(iii) Atomic transitions associated with highly ionized plasmas can be studied in a variety of laboratory experiments and astrophysical sources. Twenty-two times ionized iron (Fe^{22+}) has the same ground state configuration and term as neutral Beryllium. Explain whether you would expect the Bohr formula to provide a better or poorer prediction of the energies of the occupied 2s orbitals in the ground state of Fe^{22+} compared to how well it matches the energies for neutral Beryllium. **[4]**

[Iron has atomic number $Z = 26$.]

continued …

SECTION B

12 **(a)** Explain what is meant by the spin-orbit interaction in atomic physics and justify why the energy shift of an atomic state due to the spin-orbit interaction is expected to be of the form

$$\Delta E \propto \underline{L} \cdot \underline{S}$$

where $\underline{L}$ is orbital angular momentum and $\underline{S}$ is spin. **[10]**

(b) Prove that the energy shift due to the spin-orbit interaction can be expressed in terms of the quantum numbers L, S and J as

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

where K is a proportionality constant. **[5]**

(c) Discuss how the effects of the spin-orbit interaction can be observed in atomic spectra. **[3]**

(d) Consider the emission of photons in transitions between the $1s^2 2s^2 2p^6 3p\ {}^2P$ and $1s^2 2s^2 2p^6 3s\ {}^2S$ states of the neutral sodium atom ($Z = 11$). The mean wavelength of these transitions is 589.194 nm.

(i) Into how many different *fine-structure components* will the spin-orbit interaction split the $1s^2 2s^2 2p^6 3p\ {}^2P \rightarrow 1s^2 2s^2 2p^6 3s\ {}^2S$ transition? Explain your answer. **[4]**

(ii) Adopting $K = 7.1 \times 10^{-4}$ eV, estimate the wavelength differences between each of these fine-structure components. **[8]**

[END OF SECTION B]

continued …

SECTION C

Use a Section C answer book

Answer ONE question from this section

13 **(a)** The liquid drop model of the nucleus allows us to express the total binding energy of a nucleus of atomic mass, A, and atomic number, Z, by the following equation

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

(i) Explain the physical origins of the five terms on the right-hand side of the equation. Include comments on the scaling with A for the first three terms. **[14]**

(ii) The values of the constants, in the equation above, can be given in units of MeV as $a_v = 15.76$, $a_s = 17.8$, $a_c = 0.711$, $a_{as} = 23.7$ and $a_{oe} = \pm 34.0$ for even-even or odd-odd nuclei or $a_{oe} = 0$ for odd-even and even-odd nuclei. Using these values calculate the binding energy per nucleon for ^{56}Fe (Z=26). Calculate the energy released when ^{210}Po (Z=84) decays by alpha particle emission. **[8]**

(b) The endpoint momentum for β^+ emission from a ^{64}Cu nucleus is approximately p= 1.05 MeV/c.

(i) Convert this momentum to SI units. **[2]**

(ii) Calculate the radius in the nucleus from which the β^+ (positron) must be emitted in order to impart a quantum unit of angular momentum. How does this compare to the estimated radius of the actual nucleus? How does this affect the selection rules for β emission? **[6]**

continued …

SECTION C

14 **(a)** At short range, the internucleon force has a repulsive component that is mediated by exchange of ρ and ω particles. Assuming this part of the inter-nucleon force has a range of only 0.5 fm, estimate the mass of these particles. Clearly state any assumptions made. **[6]**

(b) An experiment is carried out where electrons with kinetic energy 400 MeV are scattered from nuclei of atomic mass number, A= 100. Treating the nuclei as flat disk targets, estimate the angle at which we see a first minimum on the diffraction pattern, stating any approximations made. **[6]**

(c) Explain why nuclei with a closed shell plus a 'spare' neutron are just as likely to show a strong quadrupole moment as nuclei with a closed shell plus a 'spare' proton. **[6]**

(d) The ^{114}Cd nucleus has $J^p= 0^+$ ground state with a $J^p=2^+$ state at 0.588 MeV and a triplet of $J^p= 0^+,2^+,4^+$ closely spaced about 1.2 MeV. Are these levels due to vibrational modes or rotational modes? Briefly explain your reasoning. **[6]**

(e) Write down an integral equation defining the quadrupole moment for a nucleus and explain why a positive value for the quadrupole moment means that the nucleus is prolate in shape. **[6]**

END OF EXAMINATION