The University Of Sheffield.

**DEPARTMENT OF PHYSICS & ASTRONOMY**

**Spring Semester 2006-2007**

**ASPECTS OF MODERN PHYSICS** **1 hour 30 minutes**

*Answer TWO questions, not more than one from each section.*

*Answers to different sections must be written in separate books, the books tied together and handed in as one.*

*A formula sheet and table of physical constants is attached to this paper.*

*All questions are marked out of ten. The breakdown on the right-hand side of the paper is meant as a guide to the marks that can be obtained from each part.*

# SECTION A – ORGANIC SEMICONDUCTORS

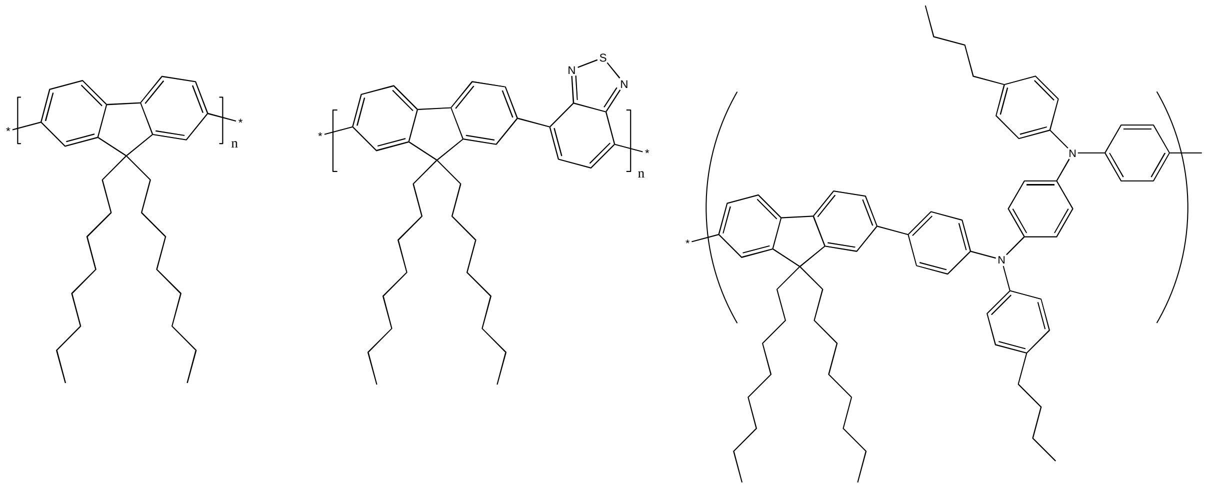
**1** (a) Carbon is able to form covalent bonds via electronic hybridization of its *s* and *p* electronic orbitals. Describe with the aid of diagrams the hybridization and the structure of $sp^3$, $sp^2$ and $sp$ hybrid orbitals. Show how such orbitals can be used to form a bond between two carbon atoms. [3]

(b) Figure 1 below shows three polyfluorene based polymers, marked A, B and C.

Identify, with reasons, which polymer has

(i) the highest hole mobility, and

(ii) the highest electron mobility. [2]



**A** **B** **C**

**Figure 1**

1 (c) The absorption and fluorescence emission spectra of the molecular dye diphenyl-anthracene in solution are shown in figure 2. Absorption is plotted using a dashed line, fluorescence using a solid line.

(i) Explain, with reference to potential energy curves, the origin of the features observed in the absorption and fluorescence spectra.

From the absorption spectrum, make an estimate of

(ii) the energy-gap of diphenyl-anthracene, and

(iii) the energy of the principal vibrational mode to which the electronic transition couples.

(iv) Explain why the absorption spectrum of a conjugated-polymer thin film is often broad and featureless whilst its emission spectrum is highly structured. [4]

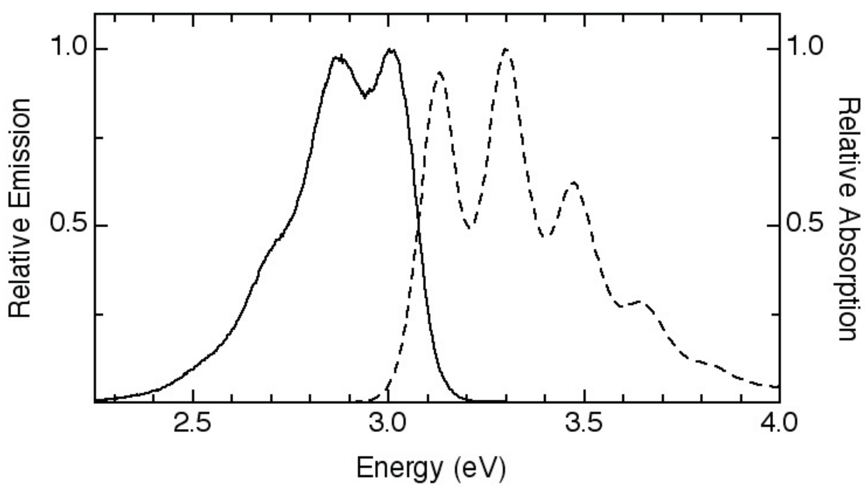



**Figure 2**

(d) A particular organic thin film has a fluorescence quantum efficiency of 45%, and an observed fluorescence decay lifetime of 300 ps. The film is left in air, which causes it to become partially oxidized (degraded) which reduces its quantum efficiency of fluorescence to 5%. What is the observed fluorescence decay lifetime of the oxidised film? [1]

**2** (a) An electron is a spin ½ particle that can be prepared in one of two spin-states: spin up $|\uparrow\rangle$ and spin down $|\downarrow\rangle$. Write down the four possible states that can be created by combining two spin ½ particles. State the total spin of each of the states and identify each state as being either a singlet or a triplet. [2]

(b) Define and describe the parameters that determine the external quantum efficiency of an organic light emitting diode (OLED). [3]

(c) With reference to your answer to parts (a) and (b) above, explain why the use of organic semiconductors containing heavy metal atoms is a promising strategy to enhance the electroluminescence quantum efficiency of an OLED. [1]

(d) The time $t$ taken for a charge carrier to travel a distance $s$ in a semiconductor under the application of an applied electric field $E$ is given by $t = s / \mu E$, where $\mu$ is carrier mobility. By treating an OLED as a simple capacitor of thickness $d$, show that the maximum current density $J$ sustainable by the OLED is given by $J \approx \varepsilon_0 \varepsilon_r \mu V^2 / d^3$. Here $V$ is the applied voltage and $\varepsilon_0$ and $\varepsilon_r$ are the permittivity of free space and the relative permittivity of the semiconductor material. [3]

(e) By making reasonable estimates for the values of the operational parameters of an OLED, calculate its typical space-charge limited current density. [1]

## SECTION B – ASTROPARTICLE PHYSICS

**3** (a) Give brief definitions of primary and secondary cosmic rays. Explain where and how secondary cosmic rays are produced. What is the composition of primary and secondary cosmic rays? Briefly describe where and how primary and secondary cosmic rays are detected and what parameters are measured. [5]

(b) Suppose several proton-induced extensive air showers with energy around $10^{20}$ eV are all detected from a certain region of the sky (and from nowhere else). What will this tell us about the distance of their source from the Earth? Explain your answer. [2]

(c) For a two neutrino model, the probability of neutrino oscillations is given by the equation

$$P_{\nu_e \to \nu_\mu} = \sin^2 2\theta \cdot \sin^2\left(\frac{1.27 \cdot D \cdot \Delta m^2}{E_\nu}\right),$$

where $\theta$ is the mixing angle, $\Delta m^2$ is the difference of squared masses in $eV^2$ of the two mass eigenstates, $D$ is the distance between the neutrino source and detector in metres and $E_\nu$ is the neutrino energy in MeV.

A reactor neutrino experiment located at a distance of 1 km from the reactor measures a flux of electron antineutrinos equal to one quarter of the expected value. Assuming the mixing angle $\theta = 45°$ and the neutrino energy $E_\nu = 2$ MeV, calculate the minimum value of $\Delta m^2$ that can explain the observed deficit. Can this value of $\Delta m^2$ be probed using solar neutrinos in the simple case of vacuum oscillations? Explain your answer. [3]

**4** (a) Write down at least three reactions by which neutrinos and antineutrinos of different flavours can be detected. [3]

(b) List four of the key design and operational requirements of a direct dark matter search experiment. [1]

(c) Describe one current or past dark matter search experiment, including detail of location, target and detection techniques used, methods of background reduction and discrimination, and results of the experiment to date. [2]

(d) In the search for dark matter what is meant by the term 'WIMP wind'? Briefly explain two potential experimental signatures of the WIMP wind (i.e. the means by which the existence of the WIMP wind could be detected experimentally). Include mention of any experiments that attempt (or have attempted) to detect each of the signatures. [4]

## SECTION C – QUANTUM OPTICS

**5** (a) In a laser cooling experiment, a laser beam propagating in the $-x$ direction is tuned near to resonance with the 852 nm transition of a beam of $^{133}Cs$ atoms emitted from an oven at 500°C and travelling in the $+x$ direction. The radiative lifetime of the transition is 32 ns.

(i) Explain the process by which the interaction between the laser and the atoms can lead to cooling of the atoms. [1]

(ii) What detuning of the laser must be used to instigate the cooling process? [1]

(iii) Estimate the time taken to bring the atoms to their lowest temperature and the distance that they would travel in this time. [1.5]

(iv) Estimate the final temperature of the atoms and their root mean square velocity, on the assumption that they are cooled to the Doppler limit temperature. [1.5]

(b) The cold atoms from the laser cooling experiment of part (a) are transferred to a magneto-optical trap consisting of a magnetic quadrupole and six counter-propagating laser beams. The magnetic field strength at a position ($x$, $y$, $z$) relative to the centre of the trap is given by

$$B = B'\left(x^2 + y^2 + 4z^2\right)^{1/2}$$

where $B'$ is a constant.

(i) Explain why the temperature achieved in the trap can be lower than the Doppler limit considered in part (a)(iv), and give a lower limit to the temperature that can be obtained. [1.5]

(ii) Explain how the trap confines the atoms, stating the value of the quantum number $M_J$ of the atoms that are caught by the trap. [1]

(iii) Explain how the technique of evaporative cooling can be used to cool the atoms to temperatures lower than that calculated in part (b)(i). [1]

(iv) On the assumption that the atoms have been cooled to temperatures below the Bose-Einstein condensation temperature, describe the procedure for inducing atomic lasing. Describe further how you would demonstrate that the atomic beam was coherent. [1.5]

**6** In a quantum cryptography experiment, Alice uses a single photon source to transmit a secret key to Bob using the BB84 protocol.

(a) Explain how Alice would encode her data onto the photon stream, and the techniques that would be used by Bob to decode it. [1.5]

(b) Explain how Alice and Bob would detect the presence of an eavesdropper who has intercepted the secret key, stating the maximum system error rate that can be tolerated in the absence of the eavesdropper. [1.5]

(c) Explain how the attenuated pulses from a laser can used as an approximate single photon source. [1]

(d) Show that, when using attenuated laser pulses, the ratio of the number of multiphoton pulses (i.e. pulses containing two or more photons) to the number of single photon pulses is equal to $\bar{n} / 2$, where $\bar{n}$ is the mean photon number per pulse. You may assume that $\bar{n} = 1$. Hence estimate the maximum data rate that could be achieved from a pulsed laser running at 100 MHz if the maximum allowable ratio of multiphoton to single photon pulses is 1%. [3]

(e) Describe how you would make a genuine single photon source and demonstrate that it only emits one photon at a time. [2]

(f) In the case of a genuine single photon source, what limits the photon emission rate that can be achieved? [1]

## SECTION D – BIOLOGICAL PHYSICS

**7** Write an account of the protein folding problem in biology. Your answer should include:

(a) an explanation of the terms primary, secondary and tertiary structure of proteins,

(b) an account of the experimental results on the unfolding and refolding of proteins in solution, and the implications of these results, and

(c) an outline of the conceptual progress made as a result of the study of the statistical mechanics of simple theoretical models of protein folding. [10]

**8** Two identical molecules of a certain protein can be considered to be spheres, of radius 3 nm, each of which has a charge of +5*e* distributed uniformly around its surface.

(a) Write down an expression, valid for separations less than 300 nm, for the electrostatic potential between the two molecules when they are in a solution of pure water. [2]

(b) How would this expression need to be modified if the proteins were in a solution that contained salts at concentrations typical for biological systems? Your answer should include an explanation of the term *Debye screening length*. [2]

(c) The Van der Waals potential between two spheres of radius $R$, whose surfaces are separated by $H$, can be written, when $H < R$, as

$$U = -\frac{AR}{12H},$$

where the Hamaker constant, $A$, can be taken to be $0.5 \times 10^{-20}$ J for proteins interacting across water.

(i) Calculate the electrostatic force and the Van der Waals force between the two protein molecules when their surfaces are separated by 1 nm. Is the net force attractive or repulsive? [4]

(ii) How, qualitatively, would you expect your answer to differ in the presence of salt at physiological concentrations? [2]

[The relative dielectric permittivity of water is 78.5.]

**END OF QUESTION PAPER**