Planck constant, $h = 6.63 \times 10^{-34}$ J s
1 eV = 1.60×10^{-19} J
Boltzmann constant, $k = 1.38 \times 10^{-23}$ J K^{-1}
Speed of light, $c = 3.00 \times 10^{8}$ m s^{-1}
Rest mass of the electron, $m_e = 9.11 \times 10^{-31}$ kg

Section A - Answer **SIX** parts of this section

1.1) Using an appropriate convention, which should be carefully described, write down the electron configuration of the ground state of an atom of aluminium, $_{13}$Al. Explain briefly the physical principles which determine the configuration.

[7 marks]

1.2) Quantitative assessment of radiation passing through a medium can be made using the equation $I = I_0 \exp(-mx)$. Explain the meaning of each term in this equation. Given that the mass attenuation coefficient of concrete for 500 keV photons is 9.0×10^{-3} m^2 kg^{-1}, determine the half-value layer of concrete for this radiation. (Density of concrete = 2.4×10^3 kg m^{-3}.)

[7 marks]

1.3) The binding energies for 1s, 2s and 3s electrons in copper are 9.5 keV, 1.2 keV and 0.1 keV, respectively. Estimate the wavelengths of CuK$_\alpha$ and CuK$_\beta$ radiation and indicate to which region of the electromagnetic spectrum these radiations belong.

[7 marks]

1.4) Explain the meaning of each of the following terms used in radiation dosimetry: (a) *exposure*; (b) *absorbed dose*; (c) *dose equivalent*. State the units in which each is measured. When ionising radiation passes through air, ion pairs are produced. The average energy required to produce one coulomb of positive (and negative) ions in air is 34 J. Determine the absorbed dose in air for unit exposure at S.T.P.

[7 marks]

1.5) In the He-Ne laser, the energy difference between the ground state and a relevant excited state of He is about 20 eV. Estimate the ratio, at equilibrium, of the numbers of helium atoms in the two states at a temperature of 20°C. Explain why *population inversion* is required in the operation of a laser. Give two methods, with brief explanations, by which population inversion may be achieved.

[7 marks]

1.6) Technetium-99, a radioisotope commonly used in nuclear medicine, is conveniently produced in a generator. What is the process in the generator that leads to the production of the technetium? Give appropriate decay schemes, including that for the product, and comment on the significance of the half-lives for practical purposes. Indicate briefly how the isotope may be used to image the skeleton of a patient.

[7 marks]

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1.7) Give reasons why a safety standard for exposure to microwave radiation should take into account both power density and frequency.

[7 marks]

1.8) In a biological system the total dielectric energy loss e''_T may be expressed as

$e''_T = e'' + \dfrac{s_s}{e_0 w}$. Define each of the terms on the right side of the equation. Show, by sketching a graph of e''_T against log(frequency), how the above equation reflects the behaviour of conductive water at frequencies less than the relaxation frequency of water.

[7 marks]

Section B - Answer **TWO** questions from this section

2) The effects of ionising radiation on biological systems are sometimes summarised in survival curves. Describe the two main types of survival curve obtained experimentally.

[4 marks]

Describe physical models of radiation effects which can be used to explain the curves, and comment on their limitations.

[8 marks]

The Poisson distribution $P_n = \dfrac{a^n e^{-a}}{n!}$ is sometimes used to assess the success of radiation therapy. Explain briefly why this is an appropriate equation and define each of its terms. In an experiment to investigate the effectiveness of a particular radiation treatment, samples of 10^8 cells were irradiated; it was found that, following a dose of 4.7 Gy, an average of 3 cells survived. Compare the probabilities that a dose of 4.7 Gy absorbed by a sample of 10^8 cells will result in the survival of 0, 1, 2 and 3 cells.Comment on your result in respect of eliminating tumours by radiation therapy.

[8 marks]

Briefly discuss the problems associated with the treatment of a deep-seated tumour in a patient. Explain how dose-response curves may be of value in planning such a treatment. Comment briefly on procedures which may be used to enhance the treatment.

[10 marks]

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3) Describe, with the aid of a diagram, the sequence of events that may lead to damage when ionising radiation interacts with biological tissue.

[8 marks]

What is the approximate minimum energy that electromagnetic radiation must have if it is to produce ionisation? Determine the wavelength and frequency of radiation of this energy.

[3 marks]

Briefly describe the three processes by which electromagnetic radiation in this energy range is absorbed by matter; include in your description, but without detailed analysis, how the energy lost by the photon can be calculated for each process.

[9 marks]

Show, with the aid of a diagram, the relative importance of the three processes in the energy range considered for absorption of electromagnetic radiation by elements with proton numbers in the range 0 to 90.

[4 marks]

Calculate the threshold wavelength of a photon if it is to generate an electron-positron pair. A 4.2 MeV photon is involved in a pair-production process, from which the positron emerges with a kinetic energy of 1.5 MeV. What is the kinetic energy of the accompanying electron? The positron loses its kinetic energy by ionisation processes, and is then annihilated by an interaction with a stationary electron. How much energy is released during the annihilation process, and in what form?

[6 marks]

4) A beam of photons is passed through a diatomic molecular gas. Describe, with the aid of clear diagrams, but no detailed analysis, the origin and main features of the vibration/rotation absorption spectrum expected.

[12 marks]

By considering the normal modes of vibration of carbon dioxide, explain how the vibration/rotation absorption spectrum of gaseous carbon dioxide differs from that of the diatomic molecule. How are the vibrational/rotational modes utilised in the operation of a carbon dioxide laser?

[7 marks]

Draw a diagram to illustrate the main components of a carbon dioxide laser. Explain briefly the significance of each one to the production of laser radiation.

[7 marks]

What is the extinction length for radiation of wavelength 10.6 μm incident on tissue? (Absorption coefficient $a_{10.6} = 9.21\ \text{cm}^{-1}$.)

[4 marks]

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5) Briefly explain why it is preferable to use coaxial-line apparatus rather than an a.c. admittance bridge to measure the complex permittivity of water at frequencies around 2 GHz.

[4 marks]

Briefly describe, with the aid of a suitable diagram, a coaxial-line cell with which the complex permittivity of water could be measured at frequencies around 2 GHz.

[8 marks]

For the TEM mode, the propagation constant g is related to the complex permittivity e by the equation $g = \frac{2p}{l_a}[-e]^{\frac{1}{2}}$, where l_a is the wavelength in air. Show that the real and imaginary parts of the permittivity are given by $e' = \frac{l_a^2}{4p^2}(b^2 - a^2)$ and $e'' = \frac{a\,b\,l_a^2}{2p^2}$, where a is the attenuation coefficient and $b = \frac{2p}{l_m}$, with l_m the wavelength in the medium.

[6 marks]

Water is studied at room temperature at a frequency of 2.2 GHz in a coaxial-line cell. It is found that the attenuation coefficient is 0.23 neper cm^{-1} and that the wavelength in the water is 1.54 cm. Calculate the complex permittivity for water at 2.2 GHz.

[8 marks]

Briefly explain how you would expect the permittivity measurement at 2.2 GHz to compare with a bridge measurement at 1 MHz.

[4 marks]

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