King's College London

UNIVERSITY OF LONDON

B.Sc. EXAMINATION

CP/MP25 Radiation Physics

January 2001

Time allowed: THREE Hours

Candidates must answer SIX parts of SECTION A, and TWO questions from SECTION B.

The approximate mark for each part of a question is indicated in square brackets.

Separate answer books must be used for each Section of the paper.

You must not use your own calculator for this paper.
Where necessary, a College Calculator will have been supplied.

TURN OVER WHEN INSTRUCTED

Planck constant, $h = 6.63 \times 10^{-34}$ J s
Boltzmann constant, $k = 1.38 \times 10^{-23}$ J K^{-1}
Rest mass of the electron, $m_e = 9.11 \times 10^{-31}$ kg
Mass of the proton, $m_p = 1.67 \times 10^{-27}$ kg
1 eV = 1.60×10^{-19} J
Speed of light, $c = 3.00 \times 10^8$ m s^{-1}
Mass of α-particle = 6.62×10^{-27} kg

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

1.1) In quantum mechanics, the state of each electron in an atom can be described by 4 quantum numbers: n, l, m and s. Explain briefly the meaning and significance of each of these quantum numbers and state the *Pauli exclusion principle*. Describe how the quantum numbers can be used to explain the periodic table of elements.

[7 marks]

1.2) What is an Auger electron? The binding energy for the K shell electrons in oxygen is 532 eV, while those for the L sub-shells are 24 eV and 7 eV. Determine the approximate energy of Auger electrons ejected from oxygen and involving the K and L shells.

[7 marks]

1.3) An electron-positron pair is created from a photon of energy 4.2 MeV in the field of a nucleus. Determine the total kinetic energy of the pair. Why is a nucleus needed before pair production can take place?

[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, and explain the relationship between the *absorbed dose* and *dose equivalent*.

[7 marks]

1.5) Explain the meaning of the *population inversion* required in the operation of a laser. Illustrate your answer quantitatively by considering electron populations associated with the energy levels involved in the laser radiation of wavelength 694.3 nm from a ruby crystal.

[7 marks]

1.6) Describe briefly the hazards associated with the incidence of laser radiation on the eye, indicating, with reasons, those regions of the spectrum which may cause damage to specific components of the eye.

[7 marks]

1.7) Define each of the terms in the following equation, which relates to dielectric dispersion in some materials:

$$\varepsilon = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + i\omega\tau}.$$

Sketch a graph of ε against log(frequency), taking care to include each of the parameters from the equation in your diagram.

[7 marks]

1.8) Explain briefly why a knowledge of the complex permittivity of tissue is useful in formulating a safety standard for exposure to microwave radiation. Explain also why factors, such as the size and shape of the body, or part of the body, should be considered in formulating microwave safety standards.

[7 marks]

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

2) Explain the meaning of the term *cross section* when applied to the scattering of photons by matter. Show that the number, N, of photons transmitted by a thin sheet of material of thickness t is $N = N_0 \exp(-n\sigma t)$, where N_0 is the number of photons incident on the sheet, n is the number density of electrons in the material and σ is the scattering cross section for one electron.

[10 marks]

Describe, with the aid of diagrams, how the scattering cross section of lead varies with energy for each of the following processes, indicating approximate energy ranges on your diagrams:

(a) photoelectric absorption;

(b) Compton scattering;

(c) pair production.

[12 marks]

The binding energy for the 1s electrons in lead is 88 keV. The mass photoelectric scattering cross section of lead for photons of energy of 86 keV is $0.15\,\mathrm{m^2\,kg^{-1}}$ while that for photons of energy 90 keV is $0.77\,\mathrm{m^2\,kg^{-1}}$. In an experiment, a beam containing photons of energy 86 keV is incident normally on a lead sheet of thickness 1 mm, and the number of photons transmitted is measured. The experiment is repeated with a beam of 90 keV photons. If scattering is dominated by the photoelectric effect, and the two beams have the same incident photon flux density, determine the ratio of the transmitted photon flux densities in the two cases. Comment on your result in terms of the numbers of electrons involved in the scattering process.
(Density of lead = $11.35 \times 10^3\,\mathrm{kg\,m^{-3}}$)

[8 marks]

3) What is meant by *linear energy transfer* (LET) as applied to a beam of charged particles passing through biological tissue?

[5 marks]

When analysed using the concepts of classical mechanics, the LET of a charged particle moving with a velocity v through a medium is proportional to $(Z/v)^2$, where Ze is the charge on the particle, with e equal to the charge on the electron. Given that the LET for 1 MeV protons in water is 270 MeV cm^{-1}, estimate the LET in water for α-particles of the same energy. Describe qualitatively how the LET of 1 MeV β-particles compares with that of 1 MeV α-particles, and hence explain the nature of the tracks left in a cloud chamber by α-particles and β-particles.

[12 marks]

Discuss briefly the significance of LET in radiation therapy, and explain why statistical analyses are essential in determining how this type of therapy is to be administered to a specific patient.

[7 marks]

In experiments where a cell preparation is exposed to a beam of charged particles, the number of cells that survive the exposure is found to follow a Poisson distribution

$$P_n = \frac{a^n e^{-a}}{n!}.$$

Explain the meaning of each symbol in this equation. In experiments on a number of cell preparations each containing 10^9 cells, a given dose is found to leave, on average, 5 surviving cells. Determine the probability that the same dose will completely eliminate a tumour containing 10^9 cells of a similar type to those used in the experiments.

[6 marks]

4) For what is the acronym *LASER* an abbreviation? What are the three main characteristics of the radiation from lasers commonly used in surgery?

[6 marks]

Describe, with relevant diagrams, the essential features which any laser must have, and explain the contribution of each one to the production of laser radiation.

[12 marks]

Explain how it is possible for a laser to operate in (a) *continuous-wave* (C-W) and (b) *pulsed* modes.

[6 marks]

Argon-ion lasers emit radiation of wavelength 488 nm. A C-W laser of this type produces an output of 50 W. What is the rate of photon emission by this laser? In a pulsed argon-ion laser, a single output pulse is rated at 50 W and lasts for 10 ns. How many photons are in the pulse?

[6 marks]

5) Explain why an a.c. bridge must be capable of measuring a complex admittance if it is to be useful in the investigation of biological liquids. Describe, with the aid of suitable diagrams, how a commercial a.c. admittance bridge would be used to measure the capacitance C and conductance G of a sample of a biological liquid between 1 and 100 MHz. Include in your answer a description and diagram of a suitable sample holder.

[13 marks]

Show that, in the expression $\varepsilon = \varepsilon' - i\varepsilon''$ for the complex permittivity, $\varepsilon' = C/K$ and $\varepsilon'' = G/(\omega K)$, where K is the cell constant and ω is the angular frequency at which the measurement is made.

[8 marks]

Explain why it is not usual to calculate a value for K, and describe how this parameter might be determined.

[5 marks]

The behaviour of water at 50 MHz is investigated with a commercial a.c. admittance bridge. It is found that the capacitance is 215 pF and the conductance 4.2 mS. Given that the cell constant is 2.66 pF, calculate the complex permittivity of water at 50 MHz.

[4 marks]