King's College London

UNIVERSITY OF LONDON

This paper is part of an examination of the College counting towards the award of a degree. Examinations are governed by the College Regulations under the authority of the Academic Board.

B.Sc. EXAMINATION

CP/MP25 Radiation Physics

Summer 1999

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

1 eV = 1.602×10^{-19} J
Planck constant, $h = 6.626 \times 10^{-34}$ J s
Speed of light, $c = 2.998 \times 10^{8}$ m s^{-1}
Mass of an α-particle = 6.645×10^{-27} kg
Rest mass of the electron, $m_e = 9.109 \times 10^{-31}$ kg = 0.511 MeV

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

1.1) Explain the significance of each of the four quantum numbers associated with an electron in an atom. What is meant by the Pauli exclusion principle? Describe briefly how the Periodic Table of elements can be developed from these concepts.

[7 marks]

1.2) A beam of photons passes through a diatomic molecular gas. Describe, with the aid of a clear diagram, the characteristics of the vibrational absorption spectrum expected. In one classical approximation, a diatomic molecule is represented as a simple harmonic oscillator of period $T = 2\pi\sqrt{(\mu/k)}$, where μ is the reduced mass of the molecule and k is the spring constant associated with the molecular bond. Use this information to estimate k for the molecular gas HCl, given that the masses of H and Cl are 1.66×10^{-27} kg and 58.9×10^{-27} kg respectively, and the frequency of the absorbed radiation is 8.67×10^{13} Hz. (Neglect rotational modes.)

[7 marks]

1.3) What is meant by *linear energy transfer* (LET) in relation to the passage of ionising radiation through matter? The LET of a charged particle moving with velocity v in a specific medium is proportional to Z^2/v^2, where Ze is the charge on the particle, e being the electronic charge. Compare the LET of a 1 MeV proton with that of a 1 MeV α-particle.

[7 marks]

1.4) What are the three characteristics of radiation measured in units of *roentgen*, *gray* and *sievert*? Explain the relationships between them.

[7 marks]

1.5) A ruby laser emits light of wavelength 0.7 μm in pulses each of which has an energy of 2.8 J. Briefly describe the mechanism by which photons are emitted. How many photons are in each pulse?

[7 marks]

1.6) Describe the decay scheme of the ^{99}Mo radionuclide generator and its radionuclide product. Briefly discuss the use of the radionuclide in imaging a patient's skeleton.

[7 marks]

1.7) By considering a parallel-plate capacitor, show that the polarisation $\boldsymbol{P}$ of a dielectric material is related to the electric field $\boldsymbol{E}$ by the relation $\boldsymbol{P} = (\varepsilon_s - 1)\varepsilon_0\boldsymbol{E}$, where the symbols have their usual meanings. (Note: $\sigma = \varepsilon_s\varepsilon_0 E$)

[7 marks]

1.8) Briefly explain what is meant by *dipolar loss* and *conductivity loss*. Write down an expression for the total dielectric loss ε_T''.

[7 marks]

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

2) Describe the sequence of events that may occur when ionising radiation enters biological tissue, and discuss the results of the interactions that occur.

[5 marks]

What is the range of energies over which electromagnetic radiation can produce ionisation? Give short accounts of the four processes by which electromagnetic radiation in this energy range is absorbed by matter. Indicate, without detailed analysis, how the energy lost by the incident photons can be calculated for each process. Draw a diagram to show the relative importance of the processes for the absorption of photons in the ionisation energy range by elements with proton numbers from 1 to 90.

[15 marks]

Determine the threshold wavelength of a photon for the production of an electron-positron pair. A 4 MeV photon is involved in a pair-production process. If the electron emerges with a kinetic energy of 1.1 MeV, what is the kinetic energy of the positron? The positron loses its kinetic energy by multiple scattering and is then annihilated by interacting with a stationary electron. How much energy is radiated, and in what form?

[10 marks]

3) Following a head-on collision between two particles, with masses m_1, m_2 and initial velocities v_1, 0, the velocity of mass m_2 is $\frac{2m_1}{m_1+m_2}v_1$. Use this information to show that the maximum energy lost by a 6 MeV α-particle in collision with an electron is 3.3 keV, while the maximum energy lost by a 6 MeV β-particle in a single collision (treated classically) with an electron is 6 MeV. Hence explain the different appearances of tracks left in a cloud chamber by α-particles and β-particles.

[10 marks]

In general, the energy lost by a non-relativistic α-particle is proportional to $1/b^2$, where b is the impact parameter. Explain the meaning of b and show that the linear energy transfer (LET) of the α-particle on passing through a material with proton number Z is given by $\frac{dE}{dx} \propto Z \ln\left(\frac{b_{\max}}{b_{\min}}\right)$. Comment on the significance of the limiting parameters in the logarithmic term.

[15 marks]

Briefly discuss the significance of LET in radiation therapy.

[5 marks]

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4) The carbon dioxide gas laser emits photons in the infra-red region of the electromagnetic spectrum.

(a) What are the characteristics of the carbon dioxide molecule that enable it to lase? Sketch the emission spectrum and explain the significance of the R and P bands.

[12 marks]

(b) List the major components of the laser and discuss the relevance of each. Why is the carbon dioxide gas in the laser usually mixed with nitrogen and helium?

[13 marks]

(c) If a characteristic wavelength of 10.6 μm is selected and is incident on tissue, to what depth will it have penetrated when 75% of its incident energy has been absorbed? (absorption coefficient $\alpha_{10.6\ \mu m}$= 9.21 cm^{-1})

[5 marks]

5) Write down the Debye equation which is often used to describe dielectric dispersion. Define the terms used in the equation. Hence show that $\varepsilon' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1+(\omega\tau)^2}$ and $\varepsilon'' = \frac{(\varepsilon_s - \varepsilon_\infty)\omega\tau}{1+(\omega\tau)^2}$.

[3 marks]

Sketch the frequency dependence of the real and imaginary parts of the permittivity for water at room temperature. Use a logarithmic frequency scale and indicate typical values for the parameters.

[5 marks]

Explain, using simple physical considerations, why the loss term (ε'') behaves as shown on your diagram.

[5 marks]

Explain why a dispersion curve for a sample of tissue is useful in helping to formulate a safety standard for exposure to microwave radiation.

[5 marks]

Explain why other factors, such as the size of the body, or a part of the body such as the head, should be considered when arriving at a view as to the safety standards for microwave radiation.

[5 marks]

When measured at a frequency of 24 GHz, the complex relative permittivity of water is found to be about 31 - j35 at room temperature. If the high-frequency limit of ε' (ε_∞) is 5.5 and the static permittivity is 81, calculate the relaxation frequency for water.

[7 marks]

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