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

CPMP25 Radiation Physics

January 2006

Time allowed: THREE Hours

Candidates should answer all SIX parts of SECTION A,
and no more than TWO questions from SECTION B.
No credit will be given for answering further questions.

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

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

TURN OVER WHEN INSTRUCTED

Physical Constants

Permittivity of free space	ε_0	=	8.854×10^{-12}	F m^{-1}
Permeability of free space	μ_0	=	$4\,\pi \times 10^{-7}$	H m^{-1}
Speed of light in free space	c	=	2.998×10^{8}	m s^{-1}
Gravitational constant	G	=	6.673×10^{-11}	$\text{N m}^{2}\text{ kg}^{-2}$
Elementary charge	e	=	1.602×10^{-19}	C
Electron rest mass	m_e	=	9.109×10^{-31}	kg
Unified atomic mass unit	m_u	=	1.661×10^{-27}	kg
Proton rest mass	m_p	=	1.673×10^{-27}	kg
Neutron rest mass	m_n	=	1.675×10^{-27}	kg
Planck constant	h	=	6.626×10^{-34}	J s
Boltzmann constant	k_B	=	1.381×10^{-23}	J K^{-1}
Stefan-Boltzmann constant	σ	=	5.670×10^{-8}	$\text{W m}^{-2}\text{ K}^{-4}$
Gas constant	R	=	8.314	$\text{J mol}^{-1}\text{ K}^{-1}$
Avogadro constant	N_A	=	6.022×10^{23}	mol^{-1}
Molar volume of ideal gas at STP		=	2.241×10^{-2}	m^{3}
One standard atmosphere	P_0	=	1.013×10^{5}	N m^{-2}

SEE NEXT PAGE

SECTION A – Answer all SIX parts of this section

1.1) Following excitation, half the atoms in a certain crystal have relaxed to the ground state in 1.3 ms. Calculate the relaxation time.

[4 marks]

1.2) Green laser radiation can be produced by frequency-doubling the 1.064 μm output from a Nd:YAG laser. Calculate the photon energy, in eV, of the green emission.

[4 marks]

1.3) The vibrational frequency ν for a diatomic molecule can be written as $\nu = \frac{1}{2\pi}\sqrt{\frac{k}{\mu}}$.

Explain the meanings of the terms k and μ.
Chlorine has two stable isotopes, ^{35}Cl and ^{37}Cl. Show that the vibration frequencies of D^{35}Cl and D^{37}Cl differ by 0.146%. (The atomic mass number of deuterium, D, can be taken as 2.)

[8 marks]

1.4) Describe briefly three processes by which gamma rays may lose energy when interacting with matter. In each case indicate the energy range in which the interaction is dominant.

[9 marks]

1.5) A non-relativistic particle with mass m_1 and kinetic energy Q_1, collides with a stationary particle having mass m_2. It transfers to that particle an energy

$$Q_2 = 4\frac{m_1 m_2}{(m_1 + m_2)^2} Q_1 .$$

Show that, for an α-particle colliding with a stationary electron,

$$Q_e \approx \frac{4 Q_\alpha m_e}{m_\alpha} .$$

Hence calculate the minimum number of collisions a 5-MeV α-particle must make with electrons in order to reduce its energy to 2 MeV. State any assumptions involved.

[8 marks]

1.6) An unshielded radioactive source produces an exposure rate of 80 R min^{-1} at 1m from the source. Calculate the exposure rate in mR hr^{-1} at the same distance when a composite shielding comprising 5 cm of lead and 30 cm of concrete is used.
For this source, the mass attenuation coefficients of lead and concrete are 0.015 m^2 kg^{-1} and 0.0089 m^2 kg^{-1}, respectively, and the densities of lead and concrete are 11.4 × 10^3 kg m^{-3} and 2.35 × 10^3 kg m^{-3}, respectively.

[7 marks]

SEE NEXT PAGE

SECTION B – Answer TWO questions

2. (a) Describe the phenomenon of *stimulated emission*.

[4 marks]

Explain what is meant by a *population inversion*, and explain why this is required for the operation of a laser.

[4 marks]

(b) Using a labelled diagram, describe the principle of operation of a generic gas laser.

[5 marks]

Hence, with reference to an energy-level diagram, discuss the operation of an Argon ion laser.

[6 marks]

(c) The Ar^{+} laser will operate at several wavelengths; explain how just one wavelength may be selected.

[3 marks]

(d) An Ar^{+} laser operating at 488 nm with a power of 1 watt has a cavity length of 1.25 m. Calculate:

(i) the spacing of the longitudinal modes in nm and MHz,

[6 marks]

(ii) the photon flux per second.

[2 marks]

3. (a) Explain what is meant by a *lossy dielectric*.

A capacitor with a lossy dielectric may be represented by a pure capacitance C in parallel with a conductance G. Show that, at frequency ω, $C = K\varepsilon'$ and $G = \omega K\varepsilon''$ where K is the capacitance without the dielectric present, and ε' and ε'' are the real and imaginary parts of the relative permittivity.

[10 marks]

(b) For microwaves in a rectangular waveguide, $\left(\frac{1}{\lambda_g}\right)^2 = \left(\frac{1}{\lambda_a}\right)^2 - \left(\frac{1}{2a}\right)^2$, where λ_g is the wavelength in the guide, λ_a is the wavelength in free space and a is the larger internal dimension of the waveguide.

Show how this equation must be modified when the waveguide is filled with a dielectric material.

[2 marks]

(c) Describe the standing-wave method for measuring the wavelength of the electric field distribution in a rectangular waveguide. Sketch the behaviour expected when the waveguide contains (i) a “perfect” dielectric and (ii) a lossy dielectric.

[10 marks]

(d) Microwaves of frequency 10.5 GHz were propagated in a rectangular waveguide with a = 25 mm. The end of the waveguide was short-circuited to produce standing waves in the waveguide. Use the equations from section (b) in the following:
(i) Calculate the distance between minima in the standing wave pattern when there is no dielectric present in the waveguide.
(ii) With a “perfect” dielectric filling the waveguide, the distance between the minima was found to be 10.4 mm. Calculate the relative permittivity of this material.

[8 marks]

4. (a) Explain what is meant by a *survival curve* in the field of radiation therapy. Data for certain groups of cells irradiated with neutrons follow the *single-hit survival curve*, and with X-rays follow the *multi-target single-hit survival curve*. Sketch the forms of these survival curves and derive expressions for the surviving fraction as a function of dose in each case.

[12 marks]

(b) Show that, for large doses, the number of cells N surviving after a dose D of X-rays is $N = N_0\, n \exp(-D/D_0)$, where N_0 is the initial number of cells. Explain the physical significances of the parameters n and D_0.

[4 marks]

(c) You may assume that, after irradiation, cell survival follows the Poisson distribution

$$P_m = \frac{a^m e^{-a}}{m\,!}.$$

Define the terms in this expression, and show how it is simplified in the case of no cells surviving.

[4 marks]

(d) A large number of batches of cell cultures were irradiated with X-rays and it was found that, on average, a fraction of 10^{-3} survived after a dose of 19.85 Gy and a fraction 2×10^{-5} survived after a dose of 28.96 Gy. The overall behaviour could be described using the multi-target single-hit survival curve.

X-rays of the same energy were used to irradiate a tumour comprising 5×10^8 similar cells. Calculate the probability of destroying this tumour after a dose of 54 Gy.

[10 marks]