King's College London

UNIVERSITY OF LONDON

B.Sc. EXAMINATION

CPMP25 Radiation Physics

January 2004

Time allowed: THREE Hours

Candidates should answer no more than 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}	$\mathrm{F\ m^{-1}}$
Permeability of free space	μ_0	=	$4\,\pi \times 10^{-7}$	$\mathrm{H\ m^{-1}}$
Speed of light in free space	c	=	2.998×10^{8}	$\mathrm{m\ s^{-1}}$
Gravitational constant	G	=	6.673×10^{-11}	$\mathrm{N\ m^{2}\ kg^{-2}}$
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}	$\mathrm{J\ K^{-1}}$
Stefan-Boltzmann constant	σ	=	5.670×10^{-8}	$\mathrm{W\ m^{2}\ K^{-4}}$
Gas constant	R	=	8.314	$\mathrm{J\ mol^{-1}\ K^{-1}}$
Avogadro constant	N_{A}	=	6.022×10^{23}	$\mathrm{mol^{-1}}$
Molar volume of ideal gas at STP		=	2.241×10^{-2}	$\mathrm{m^{3}}$
One standard atmosphere	P_0	=	1.013×10^{5}	$\mathrm{N\ m^{-2}}$

SECTION A – Answer SIX parts of this section

1.1) The electronic structure of Li (Z = 3) is written $1s^2 2s^1$. Using the same notation, write down the electronic structures of C (Z = 6) and Ge (Z = 32).

[7 marks]

1.2) The mean wavelengths for the K_α and the L_α characteristic X-rays from molybdenum are 0.07114 nm and 0.5415 nm, respectively. Stating clearly your assumptions, use this information to calculate the wavelength of the K_β X-ray.

[7 marks]

1.3) Explain the principle of *Q-switching* applied to a laser, and, with the aid of a diagram, show a method of achieving it in practice.

[7 marks]

1.4) When a target is irradiated with high-energy γ-rays, secondary γ-rays with energy 0.511 MeV may be produced. Describe the processes involved, and state any conditions necessary for the processes to occur.

[7 marks]

1.5) Explain what is meant by the half value layer (HVL) for an absorber used to attenuate a beam of γ-rays.

A collimated ^{60}Co source gives an exposure rate of 80 R min^{-1} at a certain distance from the source. Calculate the thickness of lead required to reduce the exposure rate to 2 mR hr^{-1} at the same distance. The HVL of lead for ^{60}Co radiation is 10.5 mm.

[7 marks]

1.6) Explain what is meant by a *survival curve* in the field of radiation therapy. It may be assumed that cell survival follows the Poisson distribution

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

Define the terms in this expression, and calculate the probability of no cells surviving when $a = 0.3$.

[7 marks]

1.7) Show that if complex permittivity is measured on an a.c. bridge, then

$C = K\varepsilon'$ and $G = \omega K\varepsilon''$,

where the symbols have their usual meanings.

[7 marks]

1.8) Explain what is meant by *dipole moment*. Briefly explain why many macromolecules have such a dipole moment and hence how they interact with an a.c. field.

[7 marks]

SECTION B – Answer TWO questions

2) The vibrational energy levels of a diatomic molecule may be derived by treating the molecule as a harmonic oscillator, or, more realistically, as an anharmonic oscillator. The energy levels ε_V for a harmonic oscillator are given by

$$\varepsilon_V = (V + ½)\bar{\nu}_{osc}\text{, where } \bar{\nu}_{osc} = \frac{1}{2\pi c}\sqrt{\frac{k}{\mu}}\,,$$

and, for an anharmonic oscillator, by

$$\varepsilon_V = (V + ½)\{1 - x_e(V + ½)\}\bar{\nu}_e\text{, where } \bar{\nu}_e \text{ differs slightly from } \bar{\nu}_{osc}.$$

Here $\bar{\nu}_{osc}$ and $\bar{\nu}_e$ are wavenumbers, expressed in cm^{-1}, and this requires the speed of light c to be expressed in cm s^{-1}.

(a) Explain the meanings of the symbols V, x_e, k and μ.

[4 marks]

(b) For an anharmonic oscillator, derive expressions for the transition energies of the fundamental vibration (0→1) and the first and second overtones (0→2 and 0→3, respectively).

[9 marks]

(c) For carbon monoxide the frequencies at the centres of the vibration-rotation bands are 2143 and 4260 cm^{-1} for the fundamental and first overtone, respectively. By treating CO as an anharmonic oscillator, calculate the frequency at the centre of the vibration-rotation band associated with the second overtone.

[10 marks]

(d) By using the fundamental frequency, and the harmonic oscillator approximation, calculate the "spring constant" for CO. The masses of C and O are 12 m_u and 16 m_u, respectively.

[7 marks]

3) (a) Draw a diagram illustrating the important components in a Nd:YAG laser, pumped by a semiconductor laser, and explain the function of each.

[8 marks]

(b) Sketch an energy level diagram which indicates the important transitions leading to laser emission at 1.064 μm. Explain why it is more efficient to pump the laser with a semiconductor laser than with a tungsten filament lamp.

[6 marks]

(c) The mirror separation in a certain Nd:YAG laser is 50 mm. The laser provides a continuous output of 1 watt. The output beam, with diameter 3 mm, is focused to a diffraction-limited spot using a lens of focal length 20 mm.
Calculate:

(i) The wavelength-separation of the longitudinal modes,
(ii) The number of photons per second emitted by the laser,
(iii) The power density at the focus of the lens.

[12 marks]

(d) Describe one medical application of the Nd:YAG laser.

[4 marks]

4) (a) Explain what is meant by the *impact parameter* when a heavy charged particle, with kinetic energy E, mass m ($\gg m_e$) and charge Z, interacts with a stationary electron.

[4 marks]

(b) Using a purely classical description, show that the energy transferred to the electron is

$$\Delta E = \frac{k^2 Z^2 e^4}{b^2}\frac{m}{E}$$

where $k = \dfrac{1}{4\pi\varepsilon_0}$ and b is the impact parameter.

[20 marks]

(c) For a given impact parameter, calculate the energy of a proton which would transfer the same amount of energy to an electron as an α-particle with energy 5 MeV. The rest mass of the alpha particle is $m_\alpha = 6.645 \times 10^{-27}$ kg, and you may assume that the interactions are non-relativistic.

[6 marks]

5) (a) Describe, with the aid of a suitable diagram, a coaxial cell with which the complex permittivity of a liquid can be measured between 300 MHz and 4 GHz.

[10 marks]

(b) Sketch, and briefly explain, the field pattern which would be observed in the cell at 2 GHz for:

(i) a very low loss liquid

(ii) an aqueous solution.

[10 marks]

(c) The complex permittivity of water is measured between 1 and 100 GHz at room temperature. Sketch, and briefly explain, the dispersion curve which you would expect to obtain. How can such a dispersion curve provide useful information about possible hazards of exposure to non-ionising radiation?

[10 marks]