THE UNIVERSITY OF SYDNEY

MRTY 1031 - MEDICAL RADIATION PHYSICS

JUNE 2010

Time allowed: TWO HOURS

Total marks: 90 MARKS

INSTRUCTIONS
• All questions are to be answered.
• Use the answer sheet provided for section A and the answer book for section B.
• Hand in the answers to section A and B separately at the end of the examination.

DATA

Free fall acceleration at earth's surface
Speed of sound in dry air (0°C)
Speed of light in vacuum
Permittivity of free space
Permeability of free space
Elementary charge
Electron volt
Speed of light in vacuum
Planck’s constant
Boltzmann constant
Stefan-Boltzmann constant
Rydberg constant
Atomic mass unit
Rest masses - electron
  - proton
  - neutron
  - hydrogen atom

\[ g = 9.8 \text{ m.s}^{-2} \]
\[ v = 331 \text{ m.s}^{-1} \]
\[ c = 2.998 \times 10^8 \text{ m.s}^{-1} \]
\[ \varepsilon_0 = 8.854 \times 10^{-12} \text{ C}^2\text{N}^{-1}\text{m}^{-2} \]
\[ \mu_0 = 4\pi \times 10^{-7} \text{ T.m.A}^{-1} \]
\[ e = 1.602 \times 10^{-19} \text{ C} \]
\[ 1 \text{ eV} = 1.602 \times 10^{-19} \text{ J} \]
\[ c = 2.998 \times 10^8 \text{ m.s}^{-1} \]
\[ h = 6.626 \times 10^{-34} \text{ J.s} \]
\[ k = 1.381 \times 10^{-23} \text{ J.K}^{-1} \]
\[ \sigma = 5.671 \times 10^{-8} \text{ W.m}^{-2}\text{.K}^{-4} \]
\[ R_H = 1.097 \times 10^7 \text{ .m}^{-1} \]
\[ u = 1.66054 \times 10^{-27} \text{ kg} \]
\[ m_e = 9.10938 \times 10^{-31} \text{ kg} \]
\[ m_p = 1.67262 \times 10^{-27} \text{ kg} \]
\[ m_n = 1.67493 \times 10^{-27} \text{ kg} \]
\[ m_H = 1.67353 \times 10^{-27} \text{ kg} \]
Formula Sheet

\[ T = \frac{1}{f} \]

\[ v = f \lambda \]

\[ E = hf = \frac{hc}{\lambda} \]

\[ \lambda_{\text{max}} = \frac{2.898 \times 10^{-3}}{T} \]

\[ R = \frac{V}{I} \]

\[ P = VI = I^2R = \frac{V^2}{R} \]

\[ R_{\text{total}} = R_1 + R_2 + \ldots \]

\[ \frac{1}{R_{\text{total}}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots \]

\[ F = \sigma T^4 \]

\[ F = qvB \sin \phi \]

\[ F = ll_{\perp}B = llB \sin \phi \]

\[ \frac{1}{\lambda} = R_H \left( \frac{1}{n^2_{\text{lower}}} - \frac{1}{n^2_{\text{upper}}} \right) \]

\[ p = \frac{h}{\lambda} \quad \text{or} \quad \lambda = \frac{h}{p} \]

\[ \lambda_{\text{min}} \left[ \text{nm} \right] = \frac{1.24}{kV_p} \]

\[ KE = \frac{1}{2}mv^2 = \frac{p^2}{2m} \]

\[ GPE = mgh \]

\[ E \left[ \text{ joule } \right] = E \left[ eV \right] \]

\[ H = 1000 \left( \frac{\mu_{\text{medium}}}{\mu_{\text{water}}} - 1 \right) \]

\[ F_e = k \frac{q_1q_2}{d^2} = \frac{1}{4\pi \varepsilon_0} \frac{q_1q_2}{d^2} \]

\[ E = \frac{F}{q_0} \quad \text{or} \quad F_e = qE \]

\[ I = I_0 e^{-\mu x} \]

\[ I = I_0 \frac{1}{x^2} \]

\[ \Delta \lambda = \lambda' - \lambda = \frac{h}{m_e c} (1 - \cos \phi) \]

\[ h f_{\text{max}} = KE_{\text{final}} = eV_p \]

\[ \mu = -\frac{1}{x} \log_e \left( \frac{I}{I_0} \right) \]

\[ V = \frac{U}{q_0} \quad \text{or} \quad U = q_0V \]

\[ V_b - V_a = \frac{W_{a\rightarrow b}}{q_0} = \frac{F_e d}{q_0} = ED \]

\[ \text{M.A.C.} = \frac{\mu}{\rho} \]
Section A
Please use the answer sheet provided for this section.

20 multiple choice questions (1 mark each)

Question 1
Which of the following options correctly lists different bands of the electromagnetic spectrum in order of increasing energy?
(a) Radio, ultraviolet, visible light, gamma rays
(b) Gamma ray, visible light, infrared, microwaves
(c) Microwaves, infrared, visible light, X-rays
(d) X-rays, gamma rays, ultraviolet, infrared

Question 2
Which of the following options correctly distinguishes X-rays from visible light?
(a) X rays and visible light are both ionising radiation, but X-rays have lower frequency.
(b) X rays and visible light are both electromagnetic radiation, but X-rays have shorter wavelength.
(c) X-rays have lower energy than visible light but are more likely to ionise atoms.
(d) X-rays are ionising radiation and therefore fundamentally different to visible light that is electromagnetic radiation.

Question 3
If you heat a gas so that collisions are continually bumping electrons to higher energy levels, what radiation does the gas produce when the electrons fall back to lower energy levels?
(a) an emission line spectrum
(b) thermal radiation
(c) X rays
(d) an absorption line spectrum

Question 4
If the following particles are travelling at the same speed, which has the shortest de Broglie wavelength?
(a) Uranium atom
(b) Electron
(c) Alpha particle
(d) Proton
Question 5

The diagram above shows (not correctly to scale) electron energy transitions within a hydrogen atom. Which transition represents an absorbed photon with the highest energy?
(a) A  
(b) B  
(c) C  
(d) D

Question 6

Two identical torch bulbs, X and Y, are connected to the same 9V battery as shown below. X is connected to the positive terminal and Y is connected to the negative terminal.

If you measure a current of 1.0 A flowing from the battery to the light bulbs, what is the resistance of each bulb individually?
(a) 9 ohms  
(b) 4.5 ohms  
(c) 0.22 ohms  
(d) 0.11 ohms
Question 7

A photon with a wavelength of 18.0 pm is scattered by a stationary electron through an angle of 120°. What is the wavelength of the Compton scattered photon?

(a) 19.2 pm  
(b) 20.4 pm  
(c) 21.6 pm  
(d) 22.9 pm

Question 8

The diagram below shows a cross-section view of an X-ray tube. Various ‘items’ or regions within the tube are labelled with numbers.

![Diagram of X-ray tube](image)

Which of the following statements would be most correct during normal operation of the tube?

(a) Electrons are emitted by item 4 and are focussed by item 2.  
(b) Items 5 and 6 together form the cathode.  
(c) Item 1 rotates to prevent the focal spot becoming too hot.  
(d) Item 6 is more negative than item 4.

Question 9

Which of the following statements is completely correct?

(a) In the photon spectrum of an X-ray tube, Bremsstrahlung is responsible for the broad continuum but the sharp characteristic peaks are caused by sudden deceleration of electrons by the nucleus of target atoms.  
(b) Increasing the filament current in an X-ray tube increases the filament temperature and space charge around the filament and therefore increases the tube voltage.  
(c) An X-ray tube is normally operated in the ‘space charge limited region’ because that way the tube current barely changes even if the voltage fluctuates and so the tube's behaviour is more stable.  
(d) A mammography tube is different from most other X-ray tubes because it is designed to produce lower quality, lower energy X-ray photons.
**Question 10**
Consider a beam of X-ray or gamma photons being absorbed by lead. What is the minimum photon energy required to trigger pair production?
(a) 15.9 keV per photon because this is the energy of the L edge of lead
(b) 15.9 kJ per photon because this is the energy of the L edge of lead
(c) 0.51 MeV per photon because two colliding photons must together contain energy equivalent to the rest mass of a positron and an electron
(d) 1.02 MeV per photon because each photon must contain energy equivalent to the rest mass of a positron plus an electron

**Question 11**
An X-ray photon travelling through a material interacts with an atom. The photon is scattered in a random direction and loses some (but not all) of its energy which is carried away by an electron that was knocked out of the atom. What is this process called?
(a) Compton effect
(b) Photoelectric effect
(c) Elastic scattering
(d) Bremsstrahlung

**Question 12**
As an X-ray beam containing a range of photon energies passes through a material, it experiences ‘Beam hardening’. How does this affect the X-ray beam?
(a) Intensity increases because beam quality increases.
(b) Intensity decreases and average photon energy increases.
(c) Quality increases and average photon energy decreases.
(d) Average photon energy decreases therefore beam intensity decreases.

**Question 13**
For ionising radiation absorbed by a material, what is the SI unit of absorbed dose?
(a) sievert (Sv), defined as energy (in joules) absorbed per kilogram of material multiplied by the quality factor (Q)
(b) roentgen (R), defined as $2.58 \times 10^{-4}$ coulombs of ion pairs per kilogram of material
(c) gray (Gy), defined as energy (in joules) absorbed per kilogram of material
(d) half value layer (HVL), defined as the thickness of the material that attenuates the beam intensity by half
**Question 14**

Which of the following correctly describes the effect of temperature on the conductivity of a semiconductor?

(a) changes with temperature, but it depends on the type of material
(b) always decreases with temperature
(c) is not affected by temperature
(d) always increases with temperature

**Question 15**

Which of the following statements correctly describes what happens to image quality of a radiograph when the kV setting is increased?

(a) The amount of scatter in the image increases
(b) The contrast of the image increases
(c) The dose to the patient increases
(d) The spatial resolution of the image decreases

**Question 16**

When a positive bias voltage is applied to a semiconductor diode, what happens to the current that is measured as the voltage is increased?

(a) No current is measured at all.
(b) Little or no current is measured until the breakdown voltage of the diode has been reached and then the current is high.
(c) Little or no current is measured until the barrier voltage is reached and then the current is constant with increasing voltage.
(d) Little or no current is measured until the barrier voltage is reached and then the current increases with voltage.

**Question 17**

If a wider collimator is used to increase the size of the x-ray field, what happens to scatter?

(a) Increases in magnitude
(b) Reduces in magnitude
(c) Increases in energy
(d) Stays the same
Question 18
An AP view of a hand was taken with an SID of 120 cm. The length of the second metacarpal was measured to be 66 mm on the subsequent image. If the hand had been raised on a platform for imaging which was 40 cm above the imaging plane, what is the true length of the second metacarpal?
(a) 22 mm
(b) 44 mm
(c) 55 mm
(d) 88 mm

Question 19
What is the main disadvantage of CR imaging compared to film?
(a) It takes more time per patient to take and process images.
(b) The CR plates may crack causing image artefacts.
(c) CR plates have a worse spatial resolution than film.
(d) The CR plates need to be reset using a bright light source.

Question 20
Digital Radiography refers to
(a) All imaging techniques using a computer to reconstruct images
(b) A system using a photostimulable phosphor plate
(c) An integrated x-ray and detector imaging system
(d) All systems that do not use a film/screen cassette

This is the end of Section A.
Section B
Please use the booklet provided for this section.
This section has seven (7) questions (10 marks each)

ANSWER ALL QUESTIONS

Question 1
(a) Briefly define or otherwise describe the following terms (two or three lines each):
(i) Ionisation
(ii) Electric current
(iii) Image artefact
(iv) Spatial resolution
(v) Motion blur

(b) Fill in the blank spaces in the following paragraphs using the most correct words or phrases from the following list:
saturation region kinetic energy impurity atoms
increases filament temperature pair production
decreases characteristic X-ray work function
half-value layer photoelectric absorption iron
gamma accelerating voltage elastic scattering
doping Compton scattering purification
thermionic emission space charge limited region beam hardening

Don't use a word/phrase more than once. There are unused words/phrases in the list. Don't write out the whole paragraph. Just list each of your answers labelled this way:
A (i) word/phrase, (ii) word/phrase
B (i) word/phrase, (ii) etc.

A. When a metal is heated, some electrons gain enough kinetic energy to exceed the (i) _____ and leave the surface of the metal. This process is called (ii) _____.

B. An X-ray tube is normally operated in the (i) ____. In this mode, the tube current can be increased by increasing the (ii) _____.

C. At typical diagnostic X-ray energies, only two attenuation processes are significant, (i) _____ and (ii) ____. In the first process, the incident photon does not lose all of its energy.

D. Attenuation coefficient, effective photon energy and (i) _____ are all examples of ways of characterising beam quality which normally (ii) _____ as an X-ray photon beam passes through a material.

E. The properties of an intrinsic semiconductor can be changed using the process of (i) ____. To produce an n-type material from an intrinsic semiconductor consisting of silicon atoms, you would add (ii) _____.

(10 marks)
Question 2

(a) Consider a hydrogen atom that has an electron in the \( n = 2 \) energy level.

(i) Calculate the minimum energy photon required to ionise the atom.

(ii) Calculate the minimum energy photon that could be absorbed by the atom.

In each case give the answer in electron volts and state the waveband in which it occurs (e.g. X-ray, ultraviolet, ….)

(b) The Table below represents the ground state electron configurations of some low-Z atoms in terms of shells and sub-shells.

<table>
<thead>
<tr>
<th>Element</th>
<th>Atomic Number (Z)</th>
<th>Electron configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>1</td>
<td>1s</td>
</tr>
<tr>
<td>Helium</td>
<td>2</td>
<td>1s(^2)</td>
</tr>
<tr>
<td>Lithium</td>
<td>3</td>
<td>1s(^2)2s</td>
</tr>
<tr>
<td>Beryllium</td>
<td>4</td>
<td>1s(^2)2s(^2)</td>
</tr>
<tr>
<td>Boron</td>
<td>5</td>
<td>1s(^2)2s(^2)2p</td>
</tr>
<tr>
<td>Carbon</td>
<td>6</td>
<td>1s(^2)2s(^2)2p(^2)</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>7</td>
<td>1s(^2)2s(^2)2p(^3)</td>
</tr>
<tr>
<td>Oxygen</td>
<td>8</td>
<td>1s(^2)2s(^2)2p(^4)</td>
</tr>
<tr>
<td>Fluorine</td>
<td>9</td>
<td>1s(^2)2s(^2)2p(^5)</td>
</tr>
<tr>
<td>Neon</td>
<td>10</td>
<td>1s(^2)2s(^2)2p(^6)</td>
</tr>
</tbody>
</table>

(i) How does the information in this table relate to the Bohr model of the atom (if at all)?

(ii) What is the significance of the superscripts in the electron configurations? (e.g. the 2 in 1s\(^2\))

(10 marks)
Question 3

(a) An electrostatic sandblaster is very similar in concept to the electron gun in an X-ray tube or cathode ray tube. It uses an electric field to drive small sand particles out of a nozzle at very high speeds, whereas an electron gun accelerates electrons away from a source such as a hot filament.

(i) Briefly explain the physical principles behind the acceleration of electrons in an electron gun.

(ii) Compared to the electron gun, what extra features (if any) might be essential to make the sandblaster work?

(iii) By calculating the kinetic energy of the particle, determine the potential difference (voltage) that would be necessary inside the sandblaster if it uses sand particles of mass 1.0 mg, each charged to 2.5 µC, leaving the nozzle at 50 m.s⁻¹?

(b) 

(i) With the aid of a diagram, explain why protons generally travel in a spiral path along magnetic field lines.

(ii) How would the path of an electron be different to the proton, if both are travelling at the same speed?

(10 marks)

Question 4

In each of the three graphs shown here, X-ray tube spectra (labelled w, x, y or z) are plotted to show the effect of varying one (or more) of four operating parameters of an X-ray tube.

Graph 1

Graph 2

Graph 3
The four operating parameters are:

- target material
- tube current
- tube voltage
- beam filtration

(a) For Graph 1, only one of the tube operating parameters has been varied. Identify which parameter was varied and for each spectrum w, x, y and z, state (approximately) the value of this parameter.

(b) For Graph 2, one (or more) tube operating parameters may have been varied.

i) State which parameters were varied and briefly explain how you know.
ii) State which parameters were NOT varied and briefly explain how you know.

(c) For Graph 3, only one of the tube operating parameters has been varied. A friend says that for the two spectra, the targets are probably made from different elements. If you agree, briefly explain why. If you disagree, briefly explain why, then state which parameter was varied and briefly explain how you know.

(10 marks)

Question 5

(a) You use a diagnostic X-ray beam to measure the half-value thickness of an unidentified material. You find that this thickness is 50% of the half-value thickness for water, measured using the same beam. Estimate the CT number in Hounsfield units for the unidentified material given this X-ray beam. Identify the main assumptions or approximations you employed.

(b) The total linear extinction coefficient of iron is 2.72 cm\(^{-1}\) for a monoenergetic beam of 100 keV. Calculate the half-value thickness of iron for the same beam. Identify the main assumptions or approximations you employed.

(c) In terms of the relative importance of Compton scattering and photoelectric absorption in attenuation, explain briefly why in a planar chest X-ray higher energy X-rays would be better at imaging lung tissue than lower energies.

(total - 10 marks)
Question 6
The diagram below illustrates a section of a parallel grid.

![Diagram of a parallel grid]

The grid ratio, $R$, is defined as

$$R = \frac{h}{D} \quad \text{(equation 1)}$$

(a) Define the quantity $h$ by copying the diagram into your answer and labelling $h$.
(b) Define the quantity $D$, by labelling $D$ on the diagram you drew for part (a).
(c) A grid is fabricated of 30 µm lead strips sandwiched between 300 µm aluminium strips. The strips are 2.4 mm high. What is the grid ratio of this grid?
(d) What effect does using a grid have on image quality? Why?
(e) What effect does using a grid have on patient dose? Why?
(f) Name one advantage and one disadvantage of using a focussed grid with a high grid ratio.

(10 marks)

Question 7
(a) Draw a fully labelled energy diagram of an n-type semiconductor material, as it is explained by band gap theory.
(b) Using band gap theory, explain the difference between a conductor, an insulator and a semi-conductor.
(c) Explain what happens when an electron in the valence band of an intrinsic semi-conducting material gains some thermal energy.
(d) What is happening inside a semi-conducting material when it is in thermal equilibrium with the environment?

(10 marks)

This is the end of your questions.