Matter and Radiation

1998 A/L

1) The sun can be considered as a black body. Surface temperature of the sun is 6000K, and its radius is 7.0×10^8 m.

(i) Calculate the total power radiated by the sun into space
(The Stefan constant = 5.7×10^{-8} $Wm^{-2} K^{-4}$)

(ii) What are the three regions in the electromagnetic spectrum to which most of the electromagnetic radiation emitted from the sun falls in?

(iii) At what wavelength does the sun radiate most strongly?
(Wien's constant = 2.9×10^{-3}m K)

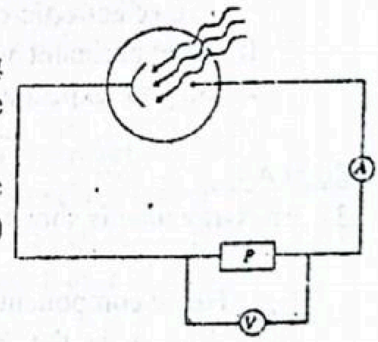
(iv) Calculate the loss of mass of the sun during an year due to the emission of electromagnetic radiation. (speed of light = 3.0×10^8 ms^{-1})

(v) Use the value calculated in (i) above, to estimate the total energy incident on the earth surface per second per square meter of area at right angles to the sun's rays. Assume that the atmosphere absorbs 10% of the energy radiated by the sun.
(The distance between the sun and the earth = 1.5×10^{11} m)

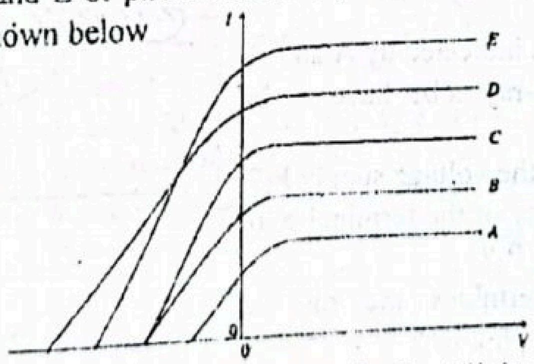
(vi) What is the rate of absorption of energy from the sun by a person lying flat on the beach on a clear day if the sun makes an angle of 30^0 with the vertical? Assume that the area of the body exposed to the sun is 0.8 m^2 and that the surface absorptivity of the skin is 0.7

1999 A/L

2) An experiment is carried out with a photoelectric cell using the circuit shown below. Here P represents a d.c. voltage supply.



By varying the intensity and frequency of the light used, five curves A.B. C. D and E of photo current (I) vs voltage (V) were obtained as shown below



(i) Which two of the curves correspond to incident light of the same frequency but of different intensities? Give the reason for your selection.

(ii) Which of the curves corresponds to the highest frequency of the light used? Give the reason for your selection.

(iii) Which of the curves corresponds to the highest intensity of the light used?

(iv) Which of the curves corresponds to the situation where the highest kinetic energy electrons are ejected from the photoelectric surface?

(v) In such an experiment the maximum kinetic energy (K_{max}) of ejected electrons by monochromatic light of frequency (f) is measured for several different values of f. the line of best fit to the experimental values of f and K_{max} is given below.

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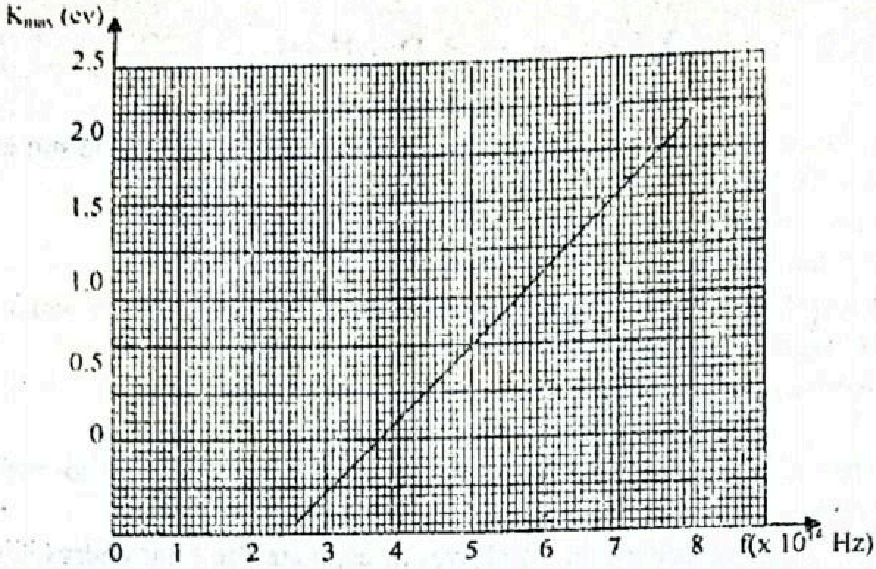


Write down an expression which relates K_{max} of f in terms of Planck constant (h) and the photo – electric work function (ϕ) of the photosensitive material.

Use the above graph to find the following:

(i) A value for the Planck constant (in Js)

(ii) Threshold frequency of the photo – electric material

(iii) Work function of the photo-electric material (in eV)

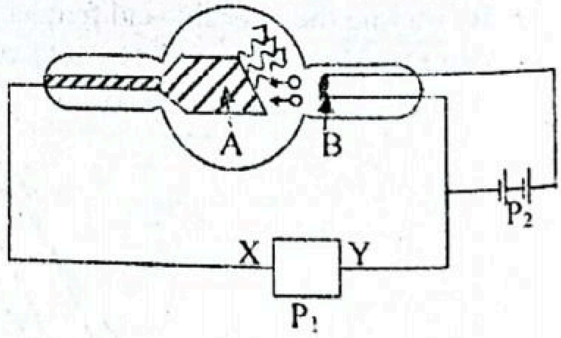
(iv) The stopping potential for $f = 7.5 \times 10^{14}$ Hz,

(electronic charge = 1.6×10^{-19} C; 1 eV = 1.6×10^{-19} J)

If the experiment was repeated with the intensity of the light source being doubled, would you expect a different straight line to that of the above? Explain your answer.

2000 A/L

3) An X-ray tube is shown in the diagram



(i) Name components indicated by A and B

(ii) Why does the X-ray tube have to be evacuated?

(iii) what is the use of the voltage supply P_2?

(iv) What is the polarity of the terminal X of the voltage supply P_1?

(v) What factor determines the rate of emission of X-ray photons?

(vi) What factor determines the energy of X-ray photons?

(vii) To produce electrons with kinetic energy of 5.6 x 10 – 15 J, what is the required voltage of the power supply P_1?

(viii) The maximum energy of the emitted X-rays is equal to the kinetic energy of the electrons hitting A. Calculate the wavelength of the X-rays having this maximum energy.

(ix) Give two applications of X-rays, related to two different fields.

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(x) In the productions of X-rays, photons are emitted due to the interaction of electrons with matter. Give a situation where electrons are produced due to the interaction of photons with matter.

Planck constant	=	6.6×10^{-34} Js
Electronic charge	=	1.6×10^{-19}C
Velocity of light	=	3.0×10^{8} ms^{-1}

2001 A/L

4) Give a labeled diagram of a set up that can be used to investigate photoelectric effect.

(i) Sketch the variation of photocurrent (I) with the potential difference (V) between the electrodes for light of fixed intensity and frequency.

Draw the expected variations of I with V for the light of

(1) same frequency but twice the intensity and (2) same intensity but a higher frequency

on your above sketch. Label situation (1) as X and situation (2) as Y

(ii) A surface of a metal is illuminated with light and photoelectrons are observed.

(1) What is the largest wavelength that will cause photoelectrons to be emitted?

(2) What is the stopping potential when light of wavelength 220 mm is used?

What is the maximum velocity of the emitted electrons?

Work function of the metal	=	4.08 eV
Mass of the electron	=	9.11×10^{-31} kg
Electronic charge	=	1.60×10^{-19} C
Velocity of light	=	3.00×10^{8} ms^{-1}
Planck constant	=	6.63×10^{-34} Js

2003 A/L

5) Read the following passage carefully and answer the questions given below.

Not all atomic nuclei are stable. Unstable nuclei transform themselves into other nuclei by spontaneous emission of α particles, β particles and γ – rays. Such unstable nuclei are said to be radioactive nuclei. This phenomenon was discovered in 1896 by a French scientist named Henri Becquerel.

The Rate of decay which is called the activity (A) of a given radioactive sample is directly proportional to the number of unstable nuclei (N) in the sample. This radioactivity law can be expressed as $A = \lambda N$, where λ (= 0.693/T) is the decay constant and T is the half –life. One important application of radioactivity is the radiocarbon dating which is a technique used for the determination of the age of fossils.

Radioactive carbon ${}^{14}_{6}C$ is being produced continuously in the Earth's atmosphere as a result of a nuclear reaction between a nitrogen ${}^{14}_{7}N$ atom in air and a cosmic ray neutron with the emission of a proton. Subsequently ${}^{14}_{6}C$ atom decays into nitrogen by emitting β^- particle with a half-life of 5730 Years (= 1.8×10^{11} s) Because of these two processes there exist an equilibrium between the rate at which ${}^{14}_{6}C$ is produced in the atmosphere and the rate at which it decays. As the composition of the Earth's atmosphere and the flux of cosmic rays have not been changed significantly in the last few thousand years, the ratio, $\dfrac{\text{number of } {}^{14}_{6}C \text{ atoms}}{\text{number of } {}^{12}_{6}C \text{ atoms}}$ Which is 10^{-12} in atmospheric carbon dioxide (CO_2) can be considered to be constant throughout this period.

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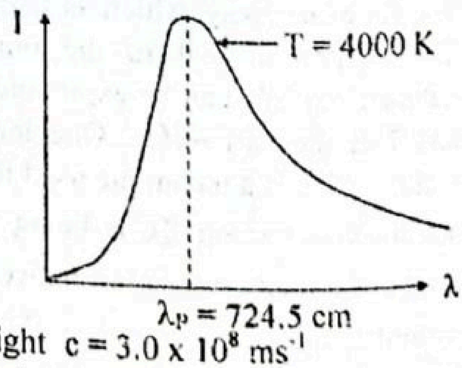
Living plants and animals take carbon from the atmosphere and hence the percentage of $^{14}_{6}C$ in plants and animals remains constant as long as they are alive. When a plant or an animal dies, the $^{14}_{6}C$ continues to decay without being replaced. As a result the percentage of $^{14}_{6}C$ decreases with time. In radioactive carbon dating the number of β^- particles given off in a certain period of time by a fixed volume of CO_2 gas in the atmosphere at a given temperature and pressure is first measured using a particle counter. Hence the activity of $^{14}_{6}C$ in the atmospheric CO_2 volume can be calculated. Then a small piece of the fossil is burnt and an equal volume of CO_2 under the same conditions is prepared. The activity of $^{14}_{6}C$ in the fossil sample can be calculated by measuring the number of β^- particles emitted from this CO_2 volume. Using the above data the age of the fossil can be determined.

(i) What is the SI unit of activity?
(ii) Write down the law of radioactivity in words
(iii) Define the half-life of a radioactive sample
(iv) What is the reason for the radioactive decay of certain nuclei?
(v) Write down the nuclear reaction corresponding to the production of $^{14}_{6}C$ in the atmosphere.
(vi) Write down the decay reaction of $^{14}_{6}C$
(vii) What are β^- and β^+ particles? What is an α particle?
(viii) Explain how the percentage of $^{14}_{6}C$ in the atmosphere remains constant.
(ix) Find the decay constant λ of $^{14}_{6}C$
(x) There are 5.0×10^{22} atoms of $^{12}_{6}C$ in 1g of carbon. If all the β^- particles emitted by a sample of 1 g of carbon of a living plant are counted, how many counts would be accumulated in one hour.
(xi) Radiocarbon dating has been used to find the age of a piece of fossil. Number of β^- counts obtained in one hour form 1g of carbon in the fossil is found to be 347. Find the age of the fossil.

2004 A/L

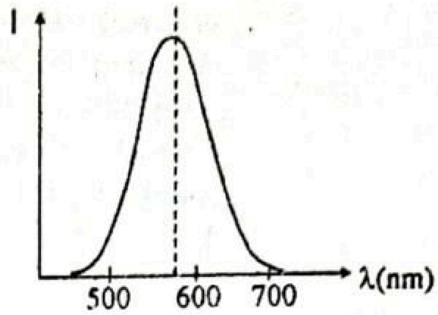
6) The intensity (I) of the radiation emitted by a black body at a temperature T = 4000 K as a function of wavelength (λ) is shown in figure. The peak of the distribution is at a wavelength (λ_p) = 724.5 nm



(i) What does the area under the curve shown in figure 1 represent?
(ii) Calculate the energy of a photon having a wavelength $\lambda = 724.5$ nm
Planck's constant $h = 6.63 \times 10^{-34}$ Js and speed of light $c = 3.0 \times 10^{8}$ ms^{-1}
(iii) (a) The wavelength λ_p corresponding to the radiation emitted by the sun is 500nm. Considering the sun to be a black body, determine its surface temperature.
(b) The radius of the sun is 7.0×10^{8} m. Calculate the total energy radiated per second by the sun. Stefan constant $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}
(c) Consider a distant star, barely visible to the naked eye at night and having properties similar to hose of the sun. If the threshold of dark – adapted vision of

the eye at wavelengths near 500 nm is 4.0×10^{-11} W m^{-2} and 40% of the total radiation emitted by the star is in the near 500 nm region, calculate the approximate distance to the star from the earth.

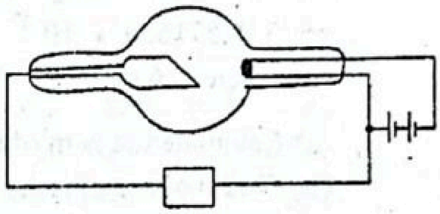
(iv) Figure 2 shows the intensity distribution of the light emitted by a firefly. The wavelength λ_p corresponding to the peak of the distribution is 570 nm. Determine the temperature of a black body that would emit the radiation peaked at the same wavelength.



Hence conclude, giving reasons, whether the radiation emitted by the firefly can be considered as black body radiation

2005 A/L.

7) i) A sketch of an X – ray tube is given in the diagram. Copy the diagram and label the target, the filament and the high voltage supply showing the correct polarity.



ii) Briefly state how the electrons inside the tube are produced ?

iii) Why should be X – ray tube be evacuated ?

iv) What is the supply voltage required to produce X – rays of maximum energy 100 ke V

v) Find the wavelength of 100 keV X – rays in Å.

vi) When X – rays go through human tissue or bone, they are absorbed mainly through photoelectric effect. The effect of X – rays on living beings (effective dose) depends on the amount of X – ray energy absorbed by a unit mass of tissue or bone. It is measured by a unit called sievert (Sv) 1S v = 1 J kg^{-1}. For persons who do not work with radiation an accumulated annual effective dose above 1 mSv is considered to be dangerous. (Effective dose due to the unavoidable background radiation is not included in this)

a) If the accumulated annual background effective dose is 2 mSv, calculate the background effective dose rate in units of $\mu Sv hr^{-1}$.

b) The maximum permissible annual effective dose for a radiation worker in an X – ray laboratory is 20 mSv. If he works 40 hours per week and 40 weeks per year, determine the average maximum affective dose rate in μ Sv hr^{-1} allowed in the X – ray laboratory for him to be safe.

c) The intensity I of an X – ray beam is normally considered as the number of photons travelling through a unit area per unit time. When exposed to an X – ray beam of intensity I, the effective dose rate H received by human tissue is given by $H = 0.57\ IEa$ μSv hr^{-1}, where E is the energy of an X – ray photon is MeV, a is the mass absorption of tissue in $cm^2\ g^{-1}$ and I is the beam intensity in $cm^{-2}\ s^{-1}$.

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i) The tissue taken to get a chest X – ray photograph is 0.1 s. If $I = 9.4\times 10^{8}$ photons $cm^{-2}\ s^{-1}$, $a = 0.027\ cm^{2}\ g^{-1}$ and E = 100 keV, determine the effective dose received by tissue when a chest X – ray is taken.

ii) Assuming that the above dose is received by a 5 kg of body tissue, calculate the number of X – ray absorbed by the tissue.

Planck's constant	$= 6.6 \times 10^{-34}$ Js
speed of light	$= 3.0 \times 10^{8}\ ms^{-1}$
1 eV	$= 1.6 \times 10^{-19}\ ms^{-1}$

2006 A/L

8) (i) Consider the decay of a radioactive ^{210}Po (polonium) atom which is at rest into a daughter atom ^{206}Pb (lead) and an $^{4}\alpha$-particle.

$$^{210}Po \rightarrow {}^{206}Pb + {}^{4}\alpha + \text{Energy } (E)$$

When E is the energy released in the decay. The atomic masses of ^{210}Po and ^{206}Pb are $348.571554 \times 10^{-27}$ kg, $341.917595 \times 10^{-27}$ kg respectively, and mass of the α-particle is 6.644625×10^{-27} kg and the speed of light is (c) $3.0 \times 10^{8}\ ms^{-1}$.

(a) Calculate the sum of the masses of the ^{206}Pb atom and the α-particle.

(b) Find the loss of mass (Δm) due to decay.

(c) E is the energy created by the mass (Δm) lost in the decay. Calculate E (Take $E = \Delta mc^2$).

(d) If the α-particle is emitted in the direction x with momentum p, what would be the magnitude and the direction of the momentum of the daughter atom.

Log tables may be used for the calculations of the following parts.

(e) The kinetic energy K of the emitted α-particle is given by $K = \frac{A_d}{A_d + A_\alpha}E$, where A_d and A_α are mass numbers of the daughter atom and the α-particle respectively. Find K.

(ii) A radioactive sample contains 1 g of polonium (^{210}Po). Decay constant (λ) of polonium for the decay in (i) above is $5.6 \times 10^{-8}\ s^{-1}$.

Find the following:

(a) the initial number (N) of ^{210}Po atoms in the sample.
(Take Avogadro constant $= 6 \times 10^{23}$ mole^{-1})

(b) the initial activity (A) of the sample ($A = \lambda N$).

(c) the initial rate of emission of α-particles.

(d) the initial rate of release of energy from the sample.

(e) (i) The half – life T of ^{210}Po in days. (Take $T = \frac{0.7}{\lambda}$ and $1\ s = 1.16 \times 10^{-5}$ days.)

(ii) Approximately by what fraction, does the activity of a given ^{210}Po sample decrease in 2 years?

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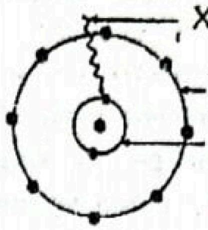
9) When an X-ray photon collides with and inner electron of an atom, (see the figure) the electron could be detached from the atom by absorbing the energy of the X-ray photon. This process of removal of electrons could be studied using the usual **photoelectric equation**. The minimum energy needed to remove an electron can be taken as the work function appearing in the photoelectric equation. At the threshold wavelength of the incident X-ray photon, the electron is just removed without imparting and kinetic energy to it.



(i) An X-ray photon of wavelength 2.2 Å could barely remove and electron at the first energy level in a Ca atom. Determine the minimum energy required (ϕ_1) to remove an electron at the first energy level in a Ca atom.

(ii) (a) When another X-ray photon with the same wavelengths as in (i) collides with and electron at the second energy level in a Ca atom and gives all its energy to it. the electron is ejected with a kinetic energy of 6.0×10^{-16} J. Calculate the minimum energy (ϕ_2) required to remove an electron at the second energy level in a Ca atom.

(b) Determine the threshold wavelength of incident X-rays to remove an electron at the second energy level in a Ca atom.

(iii) Consider the situation described in (i) above. Following the removal of an electron at the first energy level, a vacancy is created in it. An electron from the second energy level drops to the first energy level to occupy this vacancy. This transition yields a photon with energy equal to the difference between ϕ_1 and ϕ_2. Determine the wavelength of this photon. (Detection of such X-rays is used to identify heavy elements.)

(iv) The energy (E) of a photon is related to its momentum (p) by the equation $E = pc$, where c is the velocity of light.

(a) Determine the momentum of the incident X-ray photon mentioned in (i) above.

(b) Since the electron is just removed without any momentum in (i) above, the Ca atom should recoil to conserve linear momentum. Calculate the speed of the recoiling Ca atom. (The mass of Ca atom is 6.0×10^{-26} kg.)

(c) Calculate the kinetic energy of the recoiling Ca atom.

(d) Hence show that this kinetic energy is negligibly small compared to the energy of the incident X-ray photon.

$$(h = 6.6 \times 10^{-34}\ \text{Js},\ c = 3.0 \times 10^{8}\ \text{ms}^{-1},\ 1\ \text{Å} = 10^{-10}\ \text{m})$$

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10)One of the methods of measuring blood volume in human body is based on the measurement of the activity of a radioactive element added to the blood. In this method, a blood sample of known volume is removed from the body and a predetermined amount of radioactive element is added to it. This sample is then injected back into the human body. After a certain period, which is sufficient for the uniform distribution of radioactive material in the blood volume, a second blood sample is drawn and the radioactivity is measured. Blood volume can be calculated from the observed reduction of the activity.

A commonly used radioactive element in this procedure is ^{51}Cr. which has following properties.

Atomic number = 24 ; Half life = 28 d (28 days) ;

Specific activity (i.e. activity per unit mass) = 3.5×10^{15} Bq g^{-1}; Molar mass = 51 g mol^{-1}

You are also given the following constant end equations:

$$\text{Avogadro Number} = 6 \times 10^{23}\ mol^{-1} :\ T_{\frac{1}{2}} = \frac{0.7}{\lambda}\ :\ A(t) = \lambda N(t)$$

Where $T_{\frac{1}{2}}$ = Half life ; λ = Decay constant ; $N(t)$ = Number of radioactive nuclei present at time t. $A(T)$ = Active at time t

(a) Write down the number of protons and number of neutrons in a ^{51}Cr nucleus.

(b) Find the value of decay constant of ^{51}Cr in units of d^{-1} (per day).

(c) In a test to determine the blood volume of a patient of mass 70 kg, a blood sample of 10 *ml* was drawn from the patient and ^{51}Cr was added to it. If the activity inside the patient must be limited to the value 6.0×10^{4} Bq per kg of body mass after injecting the ^{51}Cr added blood sample, calculate the maximum possible mass of ^{51}Cr that can be added to 10 *ml* blood sample.

(d) A mass of 1.53×10^{-10} g of ^{51}Cr was added to the 10 *ml* blood sample. Calculate the number of ^{51}Cr nuclei added to the sample and the activity of the sample in Bq. (Take 1 day = 9×10^{4} s for your calculations.)

(e) 10 *ml* blood sample as described in part (*d*) is injected back to patient. After a sufficient time has elapsed another 10 *ml* sample was drawn from the patient and the measured activity of that sample was found to be 1000 Bq. Assuming the ^{51}Cr added to the blood sample is uniformly distributed in the patient's blood volume and neglecting the number of decayed ^{51}Cr nuclei during this time period, calculate the volume of blood in the patient's body.

(f) If the decay of ^{51}Cr is **not neglected**, will the calculated blood volume in (*e*) be slightly greater than or less than the actual value of blood volume? Explain your answer

(g) Find the time required for the activity of ^{51}Cr inside the patient to become $\frac{1}{64}$ of the initial value.

(h) Explain why a radioactive element with a half-life of 10 s is not suitable for this procedure

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11) Read the following passage and answer the questions given below.

The Sun which provides the energy necessary to sustain all forms of life on the earth, is a star in our Galaxy. At present the Sun contains about 74% hydrogen and 24% helium by mass and remaining 2% makes up some of the heavier elements. All these elements are in a completely ionized gaseous state, also known as a plasma state. The photosphere is the lowest of the three layers comprising the Sun's atmosphere and has a blackbody spectrum. Most of the visible light from the Sun comes from this photosphere which has a relatively small thickness. Immediately above the photosphere is a dim layer of less dense gas called the chromospheres. The outermost region of the Sun's atmosphere, the corona, extends several million kilometers from the chromospheres. Because the corona is the farthest region in the Sun's atmosphere from the surface of the Sun, it is expected that the temperature in that region to be the lowest. But it has been found that the highest temperature of the Sun's atmosphere which is 1.5×10^6 K, is in the coronal region. Astrophysicists have suggested that this unexpected rise in temperature of the corona is due to the release of energy carried from the interior of the Sun by complex magnetic fields that exist in the Sun.

Region below the photosphere is considered to be the interior of the Sun and has a radius of $R_\theta = 7 \times 10^8$ m, which is also considered as the solar radius and a mass $M_\theta = 2 \times 10^{30}$ kg. The region closer to the centre of the Sun where the temperature and pressure are very high is known as the core. Because of very high temperature and pressure fusion of hydrogen nuclei takes place at the core of the Sun. This hydrogen fusion reaction can be written as follows.

$$4H \longrightarrow He + 2e^+ + \text{neutrinos} + \text{energy}$$

The generated energy travels to the surface of the Sun and is released from these. When answering the following questions take Wién's constant to be 3×10^{-3} mK.

a) What is meant by the plasma state of matter?
b) What are the three regions exist in the Sun's atmosphere?
c) Which region of the Sun's atmosphere has the highest temperature? Give a reason for that region to have the highest temperature.
d) Calculate the wavelength associated with the maximum intensity of the radiation emitted from the corona. To which region of electromagnetic spectrum does this radiation belong?
e) If the wavelength corresponding to the maximum intensity of the light emitted from the photosphere is 500 nm, what is the temperature of the photosphere (i.e: the temperature of the surface of the Sun)
f) Find the energy, L_θ, released from the surface of the Sun per second which is also known as the solar luminosity. Take the Stefan constant as $\sigma = 6 \times 10^{-8}$ $Wm^{-2}K^{-4}$, and the emissivity of the solar surface as 1.
g) i) If the mass of a hydrogen nucleus is 1.67×10^{-27} kg and mass of a helium nucleus is 6.65×10^{-27} kg, calculate the mass difference (Δm) between four hydrogen nuclei and one helium nucleus. Hence calculate the energy released in a single fusion reaction using $\Delta E = (\Delta m)c^2$. Here $c = 3 \times 10^8$ ms^{-1}. Assume that the positions and neutrinos have negligible masses.

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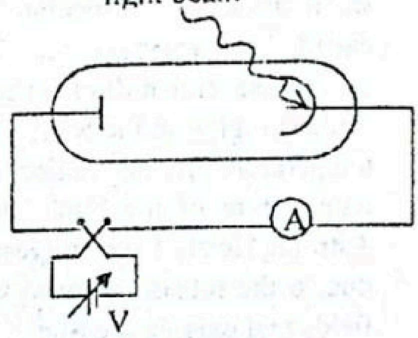
ii) Assuming that the energy released at the core of the Sun entirely contributes to the solar luminosity that you have obtained in (*i*) above, calculate the number of the hydrogen nuclei, which is converted into helium within its core each second.

iii) If it is assumed that hydrogen is converted into helium at the present rate, how long will it take to convert entire mass of hydrogen inside the Sun into helium? (For this part of the question take the mass of a hydrogen nucleus as 2×10^{-27} kg)

2010 A/L

12) The apparatus shown in the figure can be used to compare the intensities of the radiation corresponding to colours of green (frequency $f_G = 5.6 \times 10^{14}$ Hz) and violet (frequency $f_V = 7.2 \times 10^{14}$ Hz) in the electromagnetic spectrum of the Sun, incident on the Earth. The two monochromatic light beams corresponding to the two frequencies are obtained using filters. Each beam has a cross – sectional area of 5×10^{-5} m^2 and is allowed to incident normally on the photocathode, one bam at a time.



a) i) When the beam of violet light was incident on the photocathode, the stopping potential was found to be 0.05V. Calculate the work function of the photocathode material. Take Planck's constant $h = 6.6 \times 10^{-34}$ Js and the magnitude of the electronic charge, $e = 1.6 \times 10^{-19}$ C.

ii) Show that there will be no current in the circuit when green light is incident on the photocathode described in (a) (i) above.

b) i) Three other photocathodes A, B and C made of materials with work function 3.4×10^{-19} J, 5.1×10^{-19} J and 7.2×10^{-19} J respectively are available. If it is desirable to use only one photocathode to compare both green and violet light beams, which photocathode must be selected ? Give reasons for your choice.

ii) For the photocathode you selected in (b) (i) above, which colour produces

c) When photons are incident on the photocathode, only a part of the incident photons contributes for the emission of photoelectrons. Assume that 10% and 15% of incident photons emit photoelectrons for green light and violet light, respectively.

i) The maximum currents observed in the circuit for green and violet light beams are 400 μA and 240 μA respectively. Taking N_G and N_V to be the number of photons incident on the photocathode per second for green and violet colours, respectively, calculate the ratio $\frac{N_G}{N_V}$.

ii) Draw a sketch to indicate the variation of photoelectric current (I) with the applied potential difference (V), for both green colour and violet colour light, in the same graph.

iii) The average value of the energy of the solar radiation incident per unit time per unit area on the surface of the Earth is 1200 Wm^{-2} during the day time, calculate the percentage of this energy which is due to the photons corresponding to green colour.

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(13) In the medical imaging technique called positron Emission Tomography – PET) a patient is injected with a radioactive isotopes that decays by emitting positrons ^β^+ or e^+& to a blood vessel. Next, the radiation coming out of the body is detected by detectors placed around the patient. Using this information an image is constructed by a computer, which shows the concentration of that isotope in different regions of the body.

Suppose a patient is injected with 20 pico grams of ^{15}O – water (water prepared by replacing ^{16}O atoms by ^{15}O atoms). ^{15}O atoms decay by emitting positrons with a half life $\left(T_{\frac{1}{2}}\right)$ of 2 minutes. (1 pico gram = 10^{-12} gram)

(a) i) The activity of a radioactive sample that has an N number of atoms is given by the formula $A = \dfrac{0.7N}{T_{\frac{1}{2}}}$. Calculate the activity (in Bq) of the amount of ^{15}O – water injected, at the time of injection. (Take the mass of ^{15}O – water molecule is 2.8×10^{-26} kg)

ii) Calculate the activity (in Bq) inside the brain due to ^{15}O decay, after 2 minutes of the injection. Assume that 10% Bq in the body of a normal water reached the brain of the patient during that period.

iii) Due to the naturally present radioactive isotopes (such as ^{14}C) in the body, there is an activity of about 10^4 Bq in the body of a normal person. Show that 40 minutes after giving the above injection, the activity due to ^{15}O decay in the body of the patient will become less than the naturally present activity. (take $2^{20} = 10^6$)

iv) What could be the advantage of using an isotope with a very short half – life ?

(b) Inside the body, the positrons emitted by the decaying ^{15}O atoms interact with electrons in the body to produce two gamma rays according to the reaction $e^+ + e^- \rightarrow 2\gamma$. These gamma rays can be detected by detectors placed outside the body.

i) If an electron (β^-) emitting isotope is used instead of a positron (β^+) emitting isotope, explain why no radiation will come out of the body of the patient.

ii) If a gamma ray has an energy E, the magnitude p of its momentum is given by p = E/c where c is the speed of light. Using the law of conservation of momentum, show that both gamma rays in the above reaction must have the same energy and that they will be travelling in opposite directions. (assume that both e^+ and e^- have zero momentum).

iii) Both e^+ and e^- have the same mass. In energy units, this mass is 511 keV. How much is the energy of one gamma ray in the above reaction ?

(c) The maximum dose of radiation a patient could get from an ^{15}O– water injection can be estimated by assuming that all the gamma rays produced are absorbed by the body of the patient. If the weight of the patient mentioned above is 51.1 kg, calculate this maximum dose (average over the body) he could receive from the injection of 20 pico gram ^{15}O water in Gy. (1 keV = 1.6×10^{-16} J and 1 Gy = 1J kg^{-1})

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2012 A/L

14) In 1924 Louis de Broglie proposed that a particle having a linear momentum p can be described by a matter wave known as a de Broglie wave.

a) i) Write down an expression for the de Broglie wavelength (λ) in terms of the Plank constant h and p.

ii) For a particle of mass m and kinetic energy E, rewrite the above expression in terms of h, m and E.

b) A vessel is filled with helium gas at temperature T and atmospheric pressure of 10^5 Pa.

i) Write down an expression for the mean kinetic energy E of helium atoms in terms of the Boltzmann constant k and T.

ii) Using the expression derived in(a) (ii) above write down an expression for the mean de Broglie wavelength λ of helium atoms in terms of h, k, T and mass m of a helium atom.

iii) Calculate λ at T = 27°C . (The numerical values of the constants are given at the end of the question) [Take $\sqrt{8.4} = 3$]

iv) If a is the mean distance between helium atoms, by taking the total volume of helium gas to be Na^3, when N is the number of helium atoms present in the vessel determine a. Calculate helium to be an ideal gas. [Take $\sqrt[3]{60} = 4$]

v) Can the helium atoms be treated as particles under these conditions ? (Give reasons for your answer)

vi) If the volume of the gas could be decreased without changing its pressure by cooling it down, at a certain temperature T' the mean de Broglie wavelength of helium atoms can be made equal to the mean distance between helium atoms. Derive an expression for T', in terms of h, m and k.

(Plank constant $h = 6.6 \times 10^{-34}$ Js,
Mass of a helium atom $m = 6.0 \times 10^{-27}$ kg,
Boltzmann constant $k = 1.4 \times 10^{-23}$ J K^{-1})

2013 A/L

15) A photosensitive surface is illuminated by radiations of wavelength λ.

a) i) Write down the Einstein's photoelectric equation relating the maximum kinetic energy (K_{max}) of the ejected photoelectrons to λ and the work function (ϕ) of the photosensitive material.

ii) Obtain an expression for ϕ in terms of the threshold wavelength (λ_0) of the photosensitive material.

a) Plants can convert solar energy directly to chemical energy. This process is known as photosynthesis. In order to absorb light, plants use pigments known as chlorophyll. A typical chlorophyll molecule absorbs two wavelengths (one of blue colour and the other of red colour) from sunlight. The wavelengths absorbed by chlorophyll are shown in the figure (1).

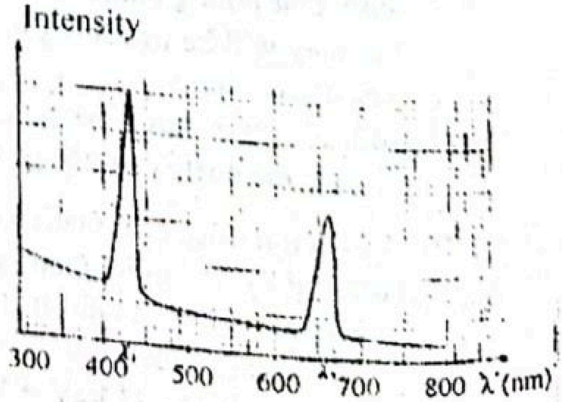

Figure (1)

i) Determine the two wavelengths, λ_1 and λ_2 absorbed by a chlorophyll molecule.
ii) Which wavelength corresponds to blue colour?

b) Chlorophyll molecules absorb the photons of the corresponding wavelengths shown in figure (1) above and get transferred to excited states. The minimum energy needed to excite the molecules is known as the excitation energy (ϕ) of the molecule. This excitation energy can be evaluated by the same expression obtained for the work function ϕ in (a) (ii) above. Determine the two excitation energies, ϕ_1 and ϕ_2 of the chlorophyll molecule, corresponding to the excitations occur due to the two absorptions λ_1 and λ_2 respectively. (Take hc = 1290 eV nm)

c) i) During the day time average rate of solar radiation incident on a unit area of the Earth's surface in Sri Lanka is 1200 W m^{-2}. Assuming that out of this rate of energy, only 0.1% belongs to the energy of the photons corresponding to the wavelength λ_1 determined in (b) (i) above, calculate the rate of energy incident on a unit surface area of the Earth, which belongs to wavelength λ_1.

ii) 1) If the effective surface area of chlorophyll molecules on a leaf of a plant is 4.0×10^{-4} m^2, determine the rate of energy incident on chlorophyll molecules, which belongs to wavelength λ_1.

2) What is the rate of photons corresponding to the rate of energy in (ii) (1) above? ($1 \text{ eV} = 1.6 \times 10^{-19}$ J)

iii) If only one chlorophyll molecule is excited for every 10^{14} photons incident on chlorophyll molecules, how many molecules are excited due to the incident photons calculated in (ii) (2) above?

iv) If such six excited chlorophyll molecules are needed to make one glucose molecule, how much time is needed to make one glucose molecule?

2014 A/L

16) Write down the expression for the Stefan-Boltzmann law of blackbody radiation. Identify each quantity of the above expression.

a) i) The sun behaves like an idealized black body. The distance from the Sun to the surface of the earth is 1.5×10^8 km. If the intensity of solar radiation flux received on the earth from the Sun is 1000 W m^{-2}, find the temperature of the Sun's surface. Neglect the temperature of the earth compared to the surface temperature of the Sun. Take the mean radius of the Sun as 7.0×10^5 km. Stefan - Boltzmann constant is 5.67×10^{-8} W m^{-2} K^{-4}.

ii) Hence, calculate the wavelength of the peak emission of radiation from the Sun at the above temperature. The Wien's displacement constant is 2.9×10^{-3} m K.

iii) A satellite orbiting the earth found that the more accurate temperature of the surface of the Sun to be 5800 K. Explain briefly the reason for the deviation of your answer from this value.

b) The sunspots are irregularly shaped small dark regions of the surface of the Sun. The dark centre of a sunspot is known as the umbra and it emits 30% of radiation compared to an equal area without sunspots on the surface of the Sun.

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i) Assuming that a sunspot also behaves as an idealized black body, calculate the temperature of the umbra of a sunspot.

ii) Calculate the shift in the wavelength of the peak emission of radiation from the umbra compared to the wavelength of peak emission of radiation from the normal surface of the Sun.

c) What changes in appearance would you expect to observe in the Sun if the number of sunspots per unit area of the Sun's surface increases significantly? Explain your answer using the blackbody radiation spectrum.

2015 A/L

17) a) Using the Einstein's mass-energy relation, determine the energy equivalence of the atomic mass unit (1 u) in MeV. ($1\ MeV = 1.6 \times 10^{-13}$ J, $1u = 1.66 \times 10^{-27}$ kg and speed of light $= 3 \times 10^{8} ms^{-1}$)

b) $^{235}_{92}U$ nucleus undergoes fission when neutron is absorbed. One of the modes of fission is given in the following reaction.

$$n + {}^{235}_{92}U \longrightarrow {}^{96}_{37}Rb + {}^{138}_{55}Cs + 2n$$

The masses of $^{235}_{92}U$, $^{96}_{37}Rb$, $^{138}_{55}Cs$ and a neutron are approximately, 235.0440 u, 95.9343 u, 137.9110 u and 1.0087 u respectively.

i) Find the mass loss of the above fission reaction in terms of atomic mass units.

ii) Hence determine the energy released in the above fission reaction in Mev.

c) In a large nuclear reactor the thermal power generated due to the fission of $^{235}_{92}U$ fuel is 3200 MW. The corresponding electrical power generated is 1000 MW. Different modes of fission reactions release different amounts of energy as heat. In these fission reactions the average heat energy generated per fission is 200 MeV.

i) Determine the deficiency of the nuclear reactor.

ii) Determine the number of fissions per second (fission rate) at the steady state of nuclear reactor.

iii) hence find the $^{235}_{92}U$ consumption rate in kg per year of the nuclear reactor. (Take Avagadro number as $6.0 \times 10^{23}\ mol^{-1}$)

d) Natural uranium contains 0.7% of $^{235}_{92}U$ and 99.3% of $^{238}_{92}U$ by weight, only $^{235}_{92}U$ is required as fuel for the above nuclear reactor to generate electricity. The above rector uranium fuel of 2% enriched uranium fuel consisting of 2% $^{235}_{92}U$ by weight.

Determine the 2% enriched uranium fuel required to run the 1000 MW reactor mentioned under (c) above for one year.

e) In coal power plants, burning of carbon produces the heat energy required to produce electricity.

$$C + O_2 \longrightarrow CO_2 + 4eV$$

The efficiency of a coal power plant is mostly the same the efficiency of a nuclear power plant. Determine the amount of carbon in kg required to run a 1000 MW coal power plant for one year. Assume that the efficiency of the coal power plant is same as efficiency determined to (c) (i) above.

(Molar mass of C $= 12\ g\ mol^{-1}$)

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2016 A/L

18) Radioisotope Thermoelectric Generator (RTGs) are used to generate electricity in space – crafts, satellites etc. An RTG consists of two subsystems.

1) **Thermal source :**
It is a container of alpha particle emitting radioactive source. The kinetic energy produced by all the alpha particles is converted to thermal energy and absorbed by the container.

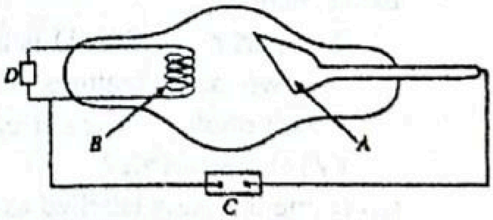
2) **Energy conversion system :**
It is a thermoelectric generator which converts thermal energy absorbed by the container into electrical energy.

Consider an RTG of a certain space – craft which uses ^{238}Pu in the form of plutonium oxide (PuO_2) as the radioactive source. The radioactive source contains 2.38 kg of PuO_2 in PuO_2 is 0.9 at the launch of the space – craft. The thermal energy absorbed per radioactive decay of ^{238}Pu by the container is 5.5 MeV. Half life of ^{238}Pu is 87.7 years and the corresponding decay constant is 0.0079 y^{-1} (= 2.5×10^{-10} s^{-1}). Avogadro number is 6.0×10^{23} atoms per mole.

i) Find the initial activity in Bq of the radioisotope source at the launch of the space - craft.
ii) If the efficiency of conversion of thermal power into electrical power is 7%. find the electrical power in the RTG at the launch of the space craft (1 MeV = 1.6×10^{-13} J).
iii) Find the activity of the radioisotope source by the end of the 10 years mission of the space - craft.
iv) Find the electrical power produced by the RTG at the end of the mission.
v) Find the percentage loss of the electrical power after the mission.
vi) Give one advantage of using RTGs in space - crafts.

2017 A/L

19)a) i) The diagram given in figure (I) is a rough sketch of an X - ray tube. Name the parts marked as A and B.



ii) Name the part marked as D and explain the purpose of using it.
iii) Name the part marked as C in the diagram and explain the purpose of using it.
iv) Explain how X - rays are produced.
v) Give a reason for using an evacuated tube.

b) The supply voltage of an X - ray tube is 100000 V.
i) Calculate the maximum energy of an electron reaching A in units of kev.
ii) An electron carrying the maximum energy calculated in (*b*) (i) above produces an X-ray photon spending half of its energy, and the rest of the energy is completely absorbed. Explain what will happen to the absorbed energy.
iii) Calculate the wavelength of the X-ray photon produced in part (*b*) (*ii*).
[$h = 6.6 \times 10^{-34}$ Js, $c = 3 \times 10^{8}$ ms^{-1} and 1 $eV = 1.6 \times 10^{-19}$ J]

c) When γ - rays pass through a material, a certain fraction of the γ - ray photons are absorbed by the material. Consider a beam of γ - rays of intensity I_0 incident perpendicular to a sheet of material of thickness t as shown in the figure (2). As a result of the absorption the transmitted intensity of the γ - ray beam is decreased, and it is denoted by I.

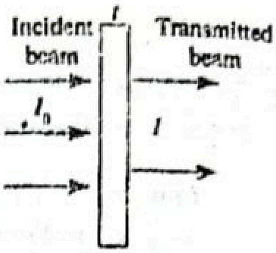


Figure (2)

The relationship between I_0 and I is given by $\log\left(\frac{I_0}{I}\right) = 0.434\ \mu t$, where μ is a constant for the material at the given γ - ray energy. All data given below are for 2 MeV γ - rays. Take value of μ for lead as 51.8 m^{-1} for 2 MeV γ - rays.

i) Calculate the thickness of lead required to reduce the intensity of the above γ - rays by half.

ii) The maximum permissible annual dose for a radiation worker is 20 mSv. When a person is exposed to the above γ - ray beam of intensity $10^{10}\ m^{-2}s^{-1}$, the annual dose received is $2.5 \times 10^6\ mSv$. Determine the maximum intensity of the above beam of γ - rays that a radiation worker can be exposed without exceeding the maximum permissible dose.

iii) Consider a radiation therapy room in a hospital, in which a 2 MeV γ - ray source is installed to treat patients. Radiation workers work in the adjacent room. The two rooms are separated by a lead wall. In case of a radiation leak in the source the maximum intensity of the γ - rays incident normal to the lead wall is $2.56 \times 10^6\ m^{-2}\ s^{-1}$. Determine the minimum thickness of the lead wall required in order for the radiation workers to work safely in their room.

2018 A/L

20)(a) The diagram given in figure (1) shows the essential parts of a setup necessary to carry out the photoelectric effect experiment.

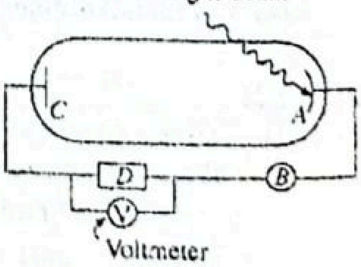


Figure (1)

(i) The part marked as D is a voltage supply. What are the two main features, D should have in order to obtain photoelectric current (I) - potential difference (V) characteristic?

(ii) Name the parts labelled as A and B.

(iii) Two monochromatic light beams, green [wavelength λ_g] and red [wavelength λ_r ($> \lambda_g$)] colours with **same** intensities measured in W m^{-2}, are allowed to incident on A, one beam at a time. The frequencies of the light beams are higher than the threshold frequency of the material made of A.

(1) Draw a rough sketch to indicate the variation of I with V, for both green and red colours in the **same** graph. The curves for green and red colours should be clearly labelled as G and R respectively. Assume that same percentage of incident green and red colour photons emit photoelectrons.

(2) If the difference between the stopping potentials is ΔV, and the difference between the frequencies is Δf for green and red colours, obtain an expression for the ratio

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$\frac{\Delta f}{\Delta V}$, in terms of Planck's constant h and magnitude of the electronic charge e using the Einstein's photoelectric effect

(b) A certain photoelectric smoke alarm system mainly consists of a T-shaped chamber fitted with a monochromatic light emitting diode (LED), a photocathode and an electronic alarm as shown in figure 2(a).

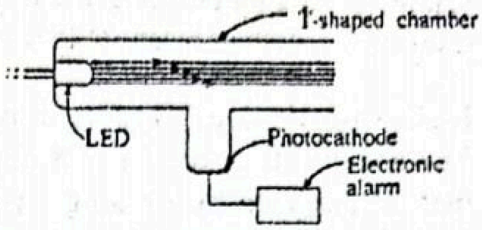

Figure 2(a)

Under the normal smoke-free condition, the photons of the LED light beam travel through the chamber and move away without striking the photocathode as shown in figure 2(a). When smoke enters the chamber, some of the photons collide with the smoke particles and move in different directions without change in their wavelength as shown in figure 2(b). The number of photons thus collides is proportional to the number of smoke particles present in the chamber. Out of the collided photons, a certain number is incident on the photocathode and generates a small photoelectric current. When a sufficient number of photons is incident on the photocathode it generates an adequate current to activate the electronic alarm.

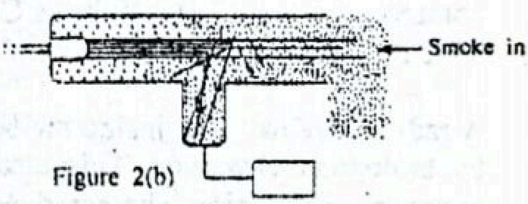

Figure 2(b)

(i) If the wavelength of the photons emitted by the LED is 825 nm, calculate the energy of a photon in eV.

Take $h = 6.6 \times 10^{-34}$ Js, speed of light in vacuum $c = 3 \times 10^{8}\ ms^{-1}$ and $1\ eV = 1.6 \times 10^{-19}$ J.

(ii) Two photocathodes X and Y, made of materials with work functions 1.4eV and 1.6eV respectively, are available to you. Which photocathode (X or Y) is suitable to construct a smoke alarm system with the LED mentioned in (b)(i) above? Justify your answer.

(iii) Power of the LED is 10 mW. If only 3% of energy goes into produce light of wavelength of 825 nm, calculate the number of photons emitted by the LED per second.

(iv) photocathode should receive at least 20% of the emitted photons per second from the LED to activate the alarm. Calculate the minimum number of photons per second that should be incident on the photocathode to activate the alarm.

(v) When photons are incident on the photocathode, only a part of the incident photons contributes to the emission of photoelectrons. Assuming that only 10% of incident photons emits photoelectrons, calculate the minimum photoelectric current that should be generated by the photocathode to activate the alarm.

Take $e = 1.6 \times 10^{-19}$ C.

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21) Read the following passage and answer the questions.

Radioactivity is a spontaneous decay process by which an unstable nucleus becomes a stable nucleus by emitting radiation. Decay rate is directly proportional to the number of radioactive atoms present at that instant but independent of external physical conditions.

Radioactive iodine ^{131}I is used in nuclear medicine to treat patients with thyroid cancer. The half-life time of ^{131}I is 8 days. It decays to stable ^{131}Xe initially by emitting a β^- particle and then by emitting a γ-photon. The maximum tissue penetration length of this β^- is 2 mm. Usually ^{131}I is administered to patients as sodium iodide ($Na^{131}I$) in the form of a capsule. Once administered, it is absorbed into the blood stream and concentrated in the thyroid gland. Radiation emitted from ^{131}I kills most of the cancer cells in the thyroid gland.

Since the patient becomes a potential source of radiation, precautions must be taken to minimize the radiation exposure to others around. The amount of radiation emitted by the patient is proportional to the activity of the dose administered. In medical practice, the common unit used for activity is Curie (Ci) which is not an SI unit. One Curie is equal to 37×10^9 disintegrations per second.

A radioactive material inside the body, diminishes not only by radioactive decay but also by biological clearance. This clearance is purely a biological process and follows an exponential variation, characterized by the decay constant λ_b. Hence the effective decay constant λ_e, due to both radioactive decay and biological clearance can be stated as $\lambda_e = \lambda_p + \lambda_b$, where λ_p is the decay constant corresponding to physical radioactive decay. The effective half – life time, which is used for radiation protection measures, is calculated from the effective decay constant.

(a) (i) State two differences between the emissions of β^- and γ.

(ii) Rewrite the following decay equation replacing a, b and c with correct numbers.

$$^{131}_{53}I \longrightarrow {}^{131}_{a}Xe + {}^{b}_{c}\beta^{-1}$$

(b) A fresh sample of $Na^{131}I$, having an activity of 100 mCi is received by a hospital. The sample is stored in a lead container at room temperature.

(i) What is the SI unit used for activity?

(ii) Write down an expression for the decay constant λ in terms of half-life time T.

(iiii) Calculate the activity of the above sample after 4 days and express the answer in SI units.
(Take ln 2 = 0.7 and $e^{-0.35} = 0.7$)

(iv) Hence, express the change in activity as a percentage.

(v) Is it possible to reduce the activity of the $Na^{131}I$ sample if it is stored at 0°C instead of storing at room temperature? Explain the answer.

(c) A small amount of $Na^{131}I$ sample having an activity of 100 mCi is administered to a thyroid patient.

(i) When dealing with such a patient, for which mode of emission, the radiation protection measures should be taken? Explain the answer.

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(ii) Show that the effective half-life time T_e of ^{131}I in thyroid gland can be given by $\frac{1}{T_e} = \frac{1}{T_p} + \frac{1}{T_b}$, where T_p and T_b are the half-life times due to radioactive decay and biological clearance, respectively.

(iii) If the biological half-life time of ^{131}I in thyroid gland is 24 days, calculate the effective half-life time of ^{131}I (in days).

(iv) Calculate the percentage change in the activity after 4 days of administration of ^{131}I
(take $e^{-0.46} = 0.63$)

(v) According to radiation protection regulations, ^{131}I treated patients can be discharged from the hospital when the activity is below or equal to 50 mCi. If this regulation is followed, how long the above ^{131}I treated patient has to be kept in isolation in the hospital before discharging?

2020 A/L

22) A monochromator is an optical instrument that can be used to produce a monochromatic beam of photons. In a photoelectric experiment a monochromatic beam of photons produced by the monochromator passes through a rectangular aperture and perpendicularly incident on a metal plate kept in a vacuum chamber as shown in the figure (1).

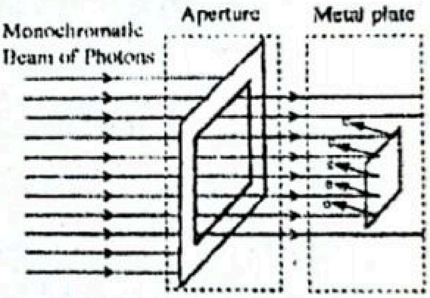

Figure (1)

Initially the monochromator produces a beam of photos of wavelength 100 nm.
Take hc = 1240 eV nm for all relevant calculations. Here h is Planck constant and c is speed of light.

a) i) Name the wavelength region of electromagnetic spectrum where the 100 nm of radiation belongs to.

ii) Calculate the corresponding energy of the 100 nm photon is eV.

iii) Considering the wave-particle duality, calculate the momentum of the photon with the above energy. ($h = 6.6 \times 10^{-34}$ Js)

b) i) Derive an expression for intensity I (energy flowing through a unit area per unit time) of a monochromatic parallel beam of n number of photons each having energy E and passing through an area A during a time t.

ii) If the intensity of 100 nm monochromatic beam of photons shown in figure (1) above is 9.92×10^{-8} Wm^{-2} and the area of the rectangular aperture is 3 mm x 4 mm, how many photons passes through the aperture per unit time? ($1 \text{ eV} = 1.6 \times 10^{-19}$ J)

iii) If the metal plate shown is a silver plate of area 2 mm x 2 mm, calculate the number of emitted photoelectrons in a unit time from the plate, assuming each incident photon emits one photoelectron.

c) i) The work function of the silver plate used in this experiment is 4.0 eV. Find the minimum and maximum values of kinetic energy of the emitted photoelectrons in eV.

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ii) The monochromator is adjusted to produce monochromatic beams of photons of wavelengths from 100 nm to 500 nm in 50 nm increments and for each wavelength, maximum kinetic energy (K_{max}) of photoelectrons emitted from the silver plate is measured. The variation of K_{max} with the wavelength of photon beam is shown in the figure (2). What are the values corresponding to points A and B?

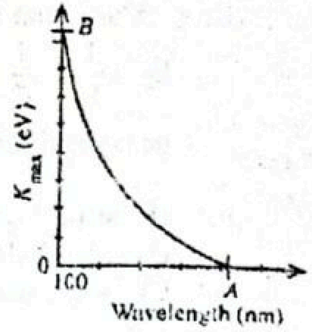

Figure (2)

iii) The same experiment is repeated for a gold plate with a work function of 5.0 eV. Copy the graph in figure (2) in your answer sheet and draw clearly the corresponding curve for the gold plate in the same graph.

iv) Same photon beam of wavelength of 200 nm is incident on both plates separately. The corresponding photocurrents measured from the silver and gold plates are i_s and i_g respectively. State whether $ig = i_s$ or $i_g > i_s$ or $i_g < i_s$. Give reason for your answer. Assume each photon incident on the plates ejects one photoelectron.

d) It has been reported that radiation of 222 nm can be used for inactivation of Covid-19 viruses. However, there is a maximum limit of 24 mJ cm – 2 per 8 hour exposure time for a human body when 222 nm radiation is used in medical applications. What should be the maximum power of a point source which emits 222 nm radiation placed 20cm from a person's Covid -19 virus contained palm? (Take $\pi = 3$)