TOPIC 26 Quantum Physics

Photoelectricity

1 The result of an experiment to investigate the energy of photoelectrons emitted from a metallic surface is represented by Fig. 1.

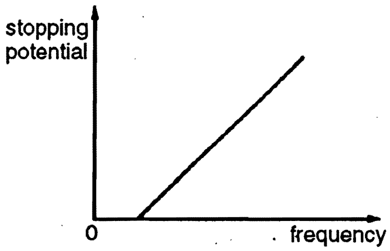


Fig. 1

The gradient of the graph depends on the

A intensity of the incident radiation.
B wavelength of the incident radiation.
C work function of the irradiated surface.
D pressure of residual gas in contact with the surface.
E ratio of the Planck constant to the electronic charge.

J76/II/14

2 Photon is the name given to

A an electron emitted from a metal surface by the action of light.
B a unit of energy,
C a positively charged atomic particle.
D an electron emitted from a metal surface by the action of heat.
E a quantum of electromagnetic radiation.

J85/I/28; N76/II/33

3 In an X-ray tube, electrons, each with a charge q, are accelerated through a potential difference V and are then made to strike a metal target. If h is the Planck constant and c is the speed of light, the minimum wavelength of the emitted radiation is given by the formula

A $\frac{hq}{cV}$ **B** $\frac{qV}{hc}$ **C** $\frac{qV}{h}$ **D** $\frac{hc}{qV}$ **E** $\frac{hcV}{q}$

N76/II/34

4 Light quanta each of energy 3.5×10^{-19} J fall on the cathode of a photocell. The current through the cell is just reduced to zero by applying a reverse voltage to make the cathode 0.25 V *positive* with respect to the anode. The minimum energy required to remove an electron from the cathode is

A 2.9×10^{-19} J
B 3.1×10^{-19} J
C 3.5×10^{-19} J
D 3.9×10^{-19} J
E 6.4×10^{-19} J

[Electron charge, $e = -1.6 \times 10^{-19}$ C.]

J77/II/15

5 The wavelength of a 5 MeV γ-ray is

A 4.95×10^{-38} m
B 8.89×10^{-32} m
C 8.89×10^{-30} m
D 2.48×10^{-13} m
E 2.48×10^{-10} m

[Electron charge = -1.6×10^{-19} C;
Planck constant = 6.6×10^{-34} J s;
speed of light = 3.0×10^{8} m s^{-1}.]

N77/II/33

6 Three energies are listed below.

1 the energy of a photon of a 3 m wavelength radio wave
2 the energy of an X-ray photon
3 the energy of a photon of yellow light from a sodium lamp

Which of the following puts these energies in order of increasing magnitude?

A	1	2	3
B	1	3	2
C	2	1	3
D	2	3	1
E	3	2	1

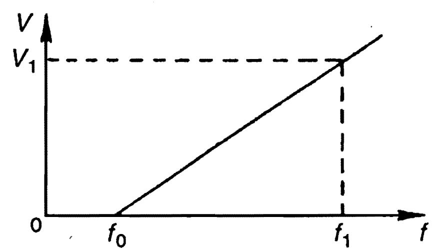
J78/II/33; N92/I/27

7 A photon of light enters a block of glass after travelling through a vacuum. The energy of the photon on entering the glass block

A increases because its associated wavelength decreases.
B decreases because the speed of the radiation decreases.
C stays the same because the speed of the radiation and the associated wavelength do not change.
D stays the same because the frequency of the radiation does not change.
E stays the same because the speed of the radiation and its wavelength increase by the same factor.

J84/II/14; N83/II/15; N78/II/13

8 In a photoelectric experiment, the potential difference V that must be maintained between the illuminated surface and the collector so as just to prevent any electrons from reaching the collector is determined for different frequencies f of the incident illumination. The graph below is obtained.

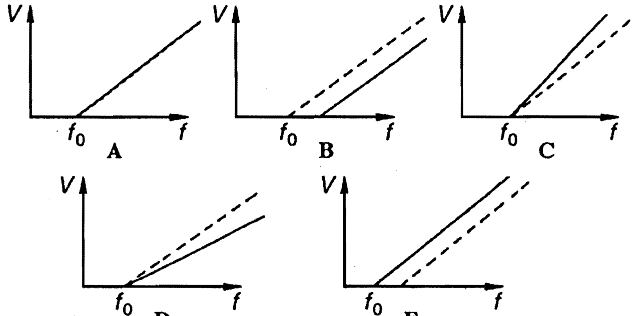


What is the maximum kinetic energy of the electrons emitted at frequency f_1? [The symbol e represents the charge on an electron and h is the Planck constant.]

A hf_1
B $V_1 / (f_1 - f_0)$
C $h(f_1 - f_0)$
D V_1
E $eV_1 / (f_1 - f_0)$

N78/II/14; J87/I/28

9 The intensity of the light used in the experiment described in question 8 is now increased and the experiment repeated. Which one of the following graphs is obtained? (The original graph is shown dotted.)



N78/II/15

10 A source emits monochromatic light of wavelength λ at power P. Given that h is the Planck constant and c the speed of light, the rate of emission of photons is

A $Pc/h\lambda$
B $\lambda c/Ph$
C $hc/P\lambda$
D $Ph/c\lambda$
E $P\lambda/hc$

J79/II/14

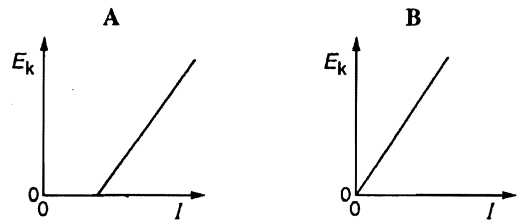
11 In a photoemission experiment, the wavelength of the light incident on the target material is increased. What is the effect of this change of wavelength on the kinetic energy of the photoelectrons produced?

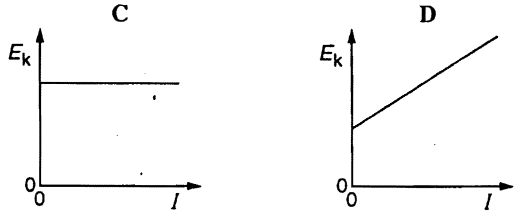
A The average kinetic energy decreases.
B The average kinetic energy increases.
C The maximum kinetic energy increases.
D The minimum kinetic energy decreases.
E The minimum kinetic energy increases.

N79/II/13; J88/I/28

12 In a photoelectric emission experiment using light of a certain frequency, the maximum kinetic energy E_k of the emitted photoelectrons is measured.

Which graph represents the way in which E_k depends on the intensity I of the light?

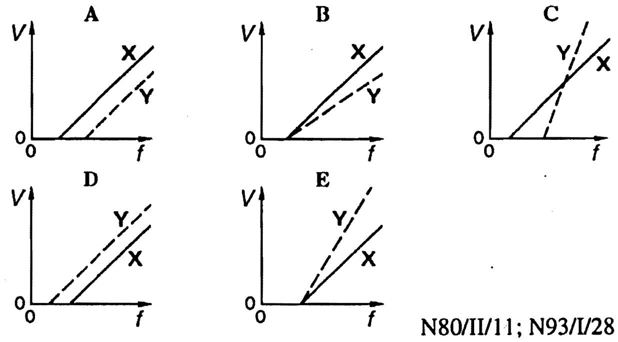




J80/II/15; N87/I/29; J99/I/28

13 In a photoelectric experiment, electrons are ejected from metals **X** and **Y** by light of frequency f. The potential difference V required to stop the electrons is measured for various frequencies.

If **Y** has a greater work function than **X**, which graph illustrates the expected results?



N80/II/11; N93/I/28

14 Which one of the following has the largest energy content?

A 10^2 photons of wavelength 1 pm (γ-rays)
B 10^5 photons of wavelength 2 nm (X-rays)
C 10^6 photons of wavelength 5 μm (infra-red radiation)
D 10^7 photons of wavelength 300 nm (ultraviolet-radiation)
E 10^8 photons of wavelength 600 nm (yellow light)

N80/II/34

15 In a series of photoelectric emission experiments, a number of metals of work functions Φ were illuminated with monochromatic light of different frequencies v and intensities I. It was found that, for each experiment, the emitted electrons emerged with a spread of kinetic energies up to a certain maximum value. This maximum kinetic energy depends on

A Φ but not on v, or I.
B Φ and I but not on v.
C Φ and v but not on I.
D v and I but not on Φ.
E Φ, v, and I.

N81/II/16

16 A beam of monochromatic radiation falls on to a metal X and photoelectrons are emitted. The rate of emission of photoelectrons will be double if

A a beam of double the intensity is used.
B radiation of double the frequency is used.
C radiation of double the wavelength is used.
D the thermodynamic temperature of the metal is doubled.
E a metal with a work function half that of X is substituted for X.

J82/II/14

17 A student connects a photocell to a supply and finds that when the cell is exposed to monochromatic radiation a current flows only when the potential difference across the cell is less than 1.6 V. What is the maximum energy of the emitted electrons?

A 1.0×10^{-19} J
B 2.6×10^{-19} J
C 4.8×10^{-11} J
D 1.6 J
E $1.0 \times 10^{+19}$ J

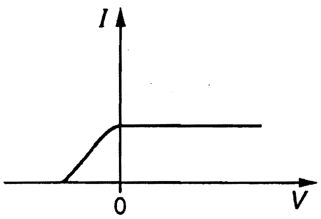
N84/II/14

18 Which one of the following statements, referring to photo-electric emission, is always true?

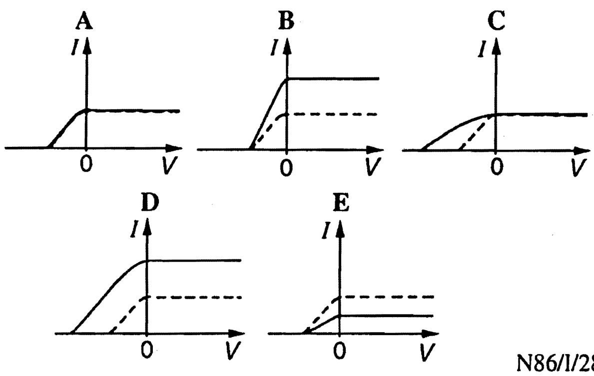
A No emission of electrons occurs for very low intensity illumination.
B For a given metal there is a minimum frequency of radiation below which no emission occurs.
C The velocity of the emitted electrons is proportional to the intensity of the incident radiation.
D The number of electrons emitted per second is independent of the intensity of the incident radiation.
E The number of electrons emitted per second is proportional to the frequency of the incident radiation.

J85/I/27

19 A metal surface in an evacuated tube is illuminated **with** monochromatic light causing the emission of photo-electrons which are collected at an adjacent electrode. For a given intensity of light, the way in which the photocurrent I depends on the potential difference V between the electrodes is as shown in the diagram below.



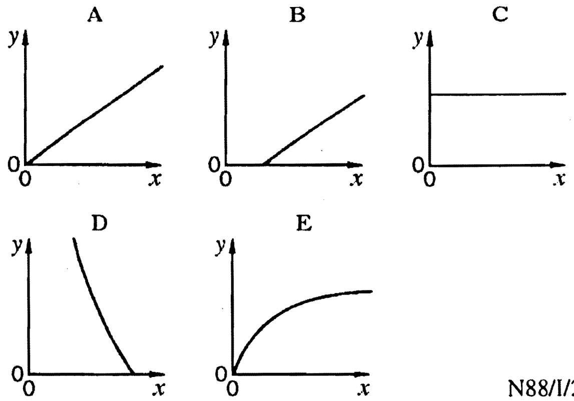
If the experiment were repeated with light of twice the intensity but the same wavelength, which of the graphs below would best represent the new relation between I and V? (In these graphs, the result of the original experiment is indicated by a broken line.)



N86/I/28

20 In an experiment on the photoelectric effect, an evacuated photocell with a pure metal cathode is used.

Which graph best represents the variation of y, the minimum potential difference needed to prevent current from flowing, when x, the frequency of the incident light, is varied?



N88/I/29

21 In experiments on the photoelectric effect, different metals were illuminated with light from various monochromatic sources of different frequencies and variable intensities. It was found that, for a given metal, frequency and intensity, electrons were emitted with a spread of kinetic energies up to a maximum value.

On what does this maximum kinetic energy depend?

	metal	*frequency of light*	*intensity of light*
A	✗	✓	✓
B	✓	✓	✗
C	✓	✗	✓
D	✓	✓	✓

N89/I/29; J98/I/28

22 When a clean metal in a vacuum is irradiated with monochromatic ultraviolet radiation, electrons are emitted. Which of the following will double if the intensity of the ultraviolet radiation is doubled?

A the maximum speed of the electrons
B the maximum kinetic energy of the electrons
C the rate of emission of the electrons
D the threshold frequency of the metal surface
E the work function of the metal surface.

J90/I/29

23 Light quanta of energy 3.5×10^{-19} J fall on the cathode of a photocell. The current through the cell is just reduced to zero by applying a stopping potential of 0.25 V.

What is the work function energy of the cathode?

A 2.9×10^{-19} J
B 3.1×10^{-19} J
C 3.5×10^{-19} J
D 3.9×10^{-19} J
E 6.4×10^{-19} J

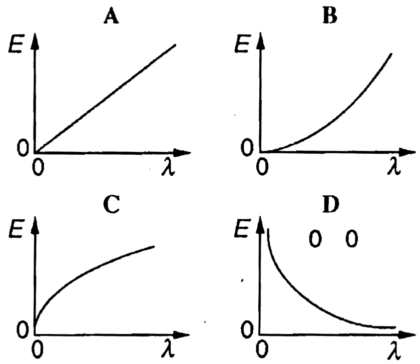
N90/I/29

24 An ultra-violet source of radiation causes the emission of electrons from a zinc plate. What would be the effect of a more intense source of the same wavelength on the maximum energy per electron, and on the number of electrons emitted per second?

	maximum energy per electron	*number of electrons emitted per second*
A	less	more
B	the same	the same
C	the same	more
D	more	the same
E	more	more

N91/I/28

25 Which graph shows how the energy E of a photon of light is related to its wavelength λ?



J92/I/29; J96/I/28

26 An ultraviolet radiation source causes the emission of photoelectrons from a zinc plate.

How would the maximum kinetic energy E_k of the photoelectrons and the number of photoelectrons emitted per second n be affected by substituting a more intense source of the same wavelength?

	E_k	n
A	decreased	increased
B	unchanged	unchanged
C	unchanged	increased
D	increased	unchanged
E	increased	increased

J92/I/30

27 Two beams, P and Q, of light of the same wavelength, fall upon the same metal surface causing photoemission of electrons. The photoelectric current produced by P is four times that produced by Q.

Which of the following gives the ratio

$$\frac{\text{wave amplitude of beam P}}{\text{wave amplitude of beam Q}}?$$

A $\frac{1}{4}$ **B** $\frac{1}{2}$ **C** 2 **D** 4 **E** 16

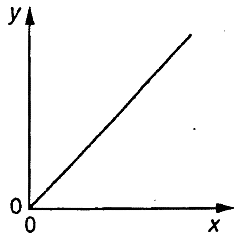
J93/I/28

28 Which of the following physical phenomena **cannot** be described only by the wave theory of electromagnetic radiation?

A diffraction
B interference
C photoelectric emission
D polarisation
E the reduction in radiation intensity with distance from a point source

N93/I/27

29 In a series of photoelectric emission experiments on a certain metal surface, possible relationships between the following quantities were investigated: threshold frequency f_0, frequency of incident light f, light intensity P, photocurrent I, maximum kinetic energy of photoelectrons T_{max}.



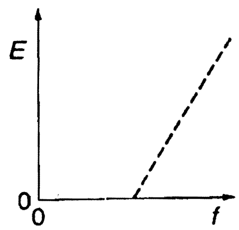
Two of these quantities, when plotted as a graph of y against x, give a straight line through the origin.

Which of the following correctly identifies x and y with the photoelectric quantities?

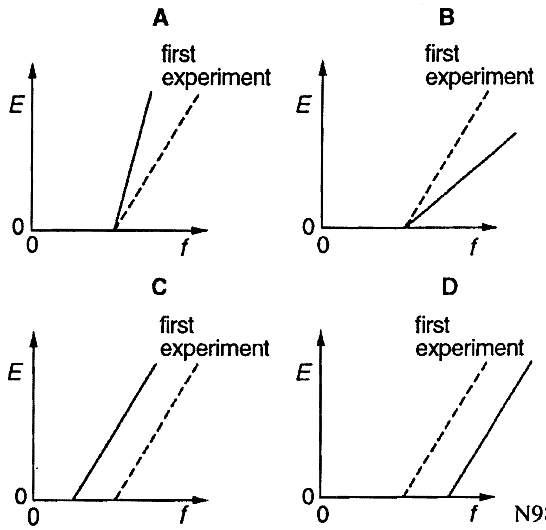
	x	y
A	I	f_0
B	f	T_{max}
C	P	I
D	P	T_{max}

N96/I/28

30 When electromagnetic radiation falls on a particular metal surface, photoelectrons may be emitted. If a graph is plotted of the maximum kinetic energy E of these electrons against frequency f of the radiation, the result is as follows.



When the experiment is repeated using another metal of greater work function energy, which graph is obtained?



N98/I/28

31 The maximum kinetic energy of photoelectrons ejected from a tungsten surface by monochromatic light of wavelength 248 nm was found to be 8.6×10^{-20} J. Find the work function of tungsten.

[The Planck constant, $h = 6.6 \times 10^{-34}$ J s; speed of light, $c = 3.0 \times 10^8$ m s^{-1} ; electronic charge, $e = -1.6 \times 10^{-19}$ C.]

N77/I/4

32 Light of photon energy 3.5 eV is incident on a plane photocathode of work function 2.5 V. Parallel and close to the cathode is a plane collecting electrode. The cathode and collector are mounted in an evacuated tube.

(a) Find the maximum kinetic energy E_{max} of photoelectrons emitted from the cathode. (Express your answer in eV.)

(b) Find the minimum value of the potential difference which should be applied between collector and cathode in order to prevent electrons of energy E_{max} from reaching the collector for electrons emitted (i) normal to the cathode, (ii) at an angle of 60° to the cathode. J79/I/3

33 In a photoelectric experiment, light of frequency 8.2×10^{14} Hz falls on a metal surface in a vacuum tube. It is found that the maximum kinetic energy of the emitted electrons is 1.2 eV. Find the work function of the metal and outline briefly how the maximum kinetic energy of the electrons could be measured. N81/I/5

34 A vacuum photoemissive cell in which the emitter and collector are of the same metal is connected in the circuit shown in Fig. 3(a). The emitter is illuminated with monochromatic radiation of wavelength 365 nm and the current I in the circuit is measured for various values of the applied potential difference V between collector and emitter. The results are shown in the graph in Fig. 3(b).

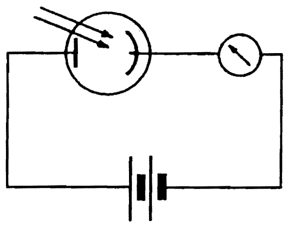


Fig. 3(a)

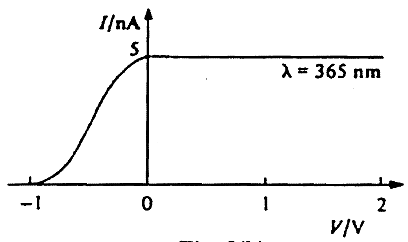


Fig. 3(b)

(a) Find the maximum kinetic energy of the photoelectrons.

(b) Deduce the work function of the emitter. (Express your answer in volts.)

(c) If the experiment were repeated using monochromatic radiation of wavelength 313 nm, where would the new graph meet the V-axis? N83/I/6

35 In a photoelectric emission experiment a metal surface in an evacuated tube was illuminated with monochromatic light. If the experiment were repeated with light of the *same* wavelength, but of *twice* the intensity, how would this affect

(a) the photon energy,

(b) the maximum kinetic energy of the photoelectrons,

(c) the work function of the metal,

(d) the photocurrent? J86/II/7

36 Find the energy of a photon of electromagnetic radiation of wavelength 0.15 nm. In which region of the electro-magnetic spectrum is this radiation? N86/II/6

37 When light of frequency 8.22×10^{14} Hz is incident on the surface of caesium metal, it is found that the maximum kinetic energy of the emitted electrons is 2.00×10^{-19} J.

Calculate the threshold frequency for photoelectric emission from caesium.

In which region of the electromagnetic spectrum does the incident frequency lie? [4] N87/II/6

38 Calculate approximate values for the maximum and minimum energies of photons of visible light. [4] J89/II/7

39 Light of wavelength 436 nm is used to illuminate the surface of a piece of clean sodium metal in a vacuum.

(a) Calculate the energy of a photon of light of this wavelength.

(b) Use your answer to *(a)* to determine the maximum energy of the photoelectrons if the maximum wavelength of light which can produce photoelectrons from sodium is 650 nm. [5] N89/II/5

40 *(a)* What is meant by the term *threshold frequency* as applied to the photoelectric effect? [1]

(b) Explain why the maximum possible kinetic energy of a photoelectron is independent of the intensity of the incident light. [2]

(c) Ultra-violet radiation of frequency 4.83×10^{15} Hz is incident on a metal surface and the resulting photoelectrons have a maximum kinetic energy of 1.28×10^{-18} J. Calculate

(i) the energy of a photon of this radiation,

(ii) the maximum kinetic energy of the photoelectrons produced by radiation of frequency 6.76×10^{15} Hz incident on the same metal surface. [6] J90/II/7

41 *(a)* (i) What is a *photon*?

(ii) Show that E, the energy of a photon, is related to λ, its wavelength, by

$$E\lambda = 1.99 \times 10^{-16},$$

where E is measured in J and λ is measured in nm. [5]

(b) Two metal electrodes A and B are sealed into an evacuated glass envelope and a potential difference V, measured using the voltmeter, is applied between them as shown in Fig. 4.

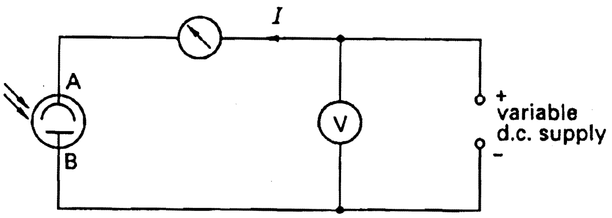


Fig. 4

B is then illuminated with monochromatic light of wavelength 365 nm and I, the current in the circuit, is measured for various values of V. The results are shown in Fig. 5.

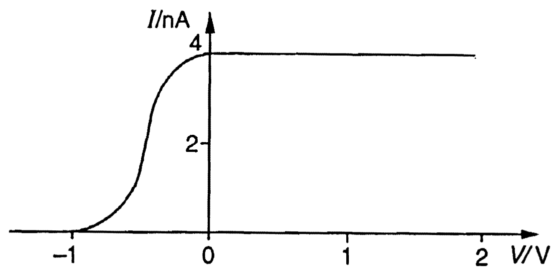


Fig. 5

(i) From this graph, deduce the p.d. required to stop photoelectric emission from B.

(ii) Calculate the maximum kinetic energy of the photoelectrons.

(iii) Deduce the work function energy of B. [5]

J91/II/7

42 In order to investigate the photo-electric effect, a student set up the apparatus illustrated in Fig. 6.

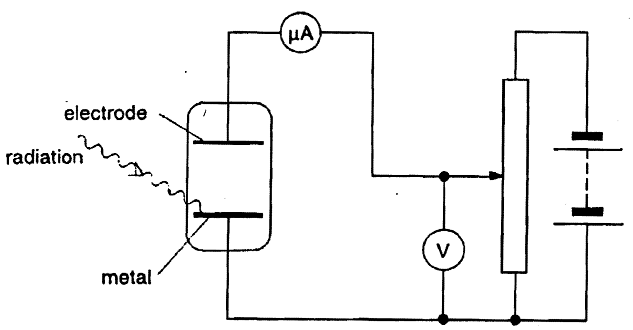


Fig. 6

The wavelength of the radiation incident on the metal surface was varied. For two values of wavelength λ, the stopping voltage V_S required just to prevent electrons reaching the electrode was measured. The results are shown in Fig. 7.

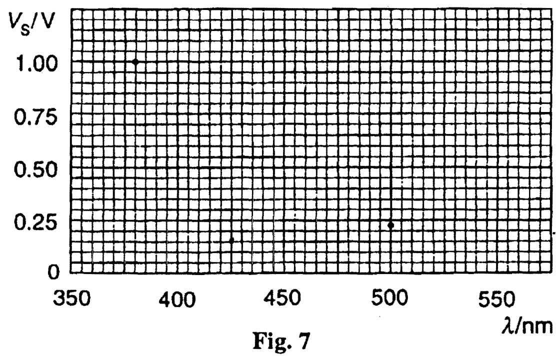


Fig. 7

(a) What is the maximum kinetic energy of a photo-electron emitted from the metal surface by radiation of wavelength 380 nm? [2]

(b) Calculate the energy of a photon of wavelength 380 nm. [2]

(c) Using your answers to *(a)* and *(b)*, calculate

(i) the work function energy of the metal surface,

(ii) the threshold wavelength. [3]

(d) Suggest why it is not possible to deduce the threshold wavelength of this metal surface directly from Fig. 7.

[1] J95/II/7

43 Electromagnetic radiation is incident normally on the surface of a metal. Electrons are emitted from the surface and these are attracted to a positively charged electrode, as shown in Fig. 8.

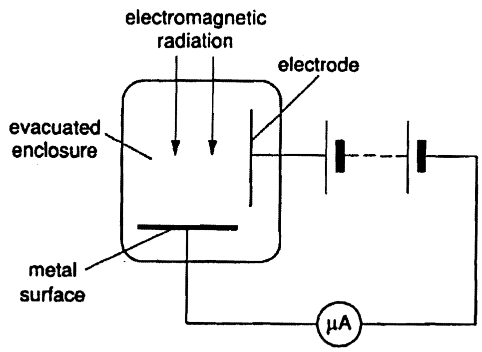


Fig. 8

(a) Name the effect which gives rise to the emission of the electrons. [1]

(b) State a word equation, based on the principle of conservation of energy, which describes this effect... [2]

(c) The current recorded on the microammeter is 2.1 μA. Calculate the number of electrons emitted per second from the surface.

number per second =...................................... [2]

(d) The incident radiation has wavelength 240 nm. Calculate the energy of a photon incident on the surface.

energy = ...J [2]

(e) The intensity of the incident radiation is 8.2×10^3 Wm^{-2}. The area of the surface is 2.0 cm^2. Calculate

(i) the power of the radiation incident on the surface,

power =..W

(ii) the number of photons incident per second on the surface.

number per second =..

(iii) Hence determine the ratio

$$\frac{\text{number of electrons emitted per second}}{\text{number of photons incident per second}}$$

ratio =.. [4]

(f) Comment on your answer to (e)(iii). [1]

J97/II/6

44 (a) A source of ultra-violet light has wavelength 2.55×10^{-7}m. Calculate the energy of a photon of this wavelength. [2]

(b) The source referred to in (a) illuminates a zinc plate which has been cleaned and placed a few millimetres beneath a piece of gauze as shown in Fig. 9. Photo-electrons are emitted from the plate and are attracted to the positive gauze because of the potential difference V between the plate and the gauze. When V is varied it is found that the photoelectric current varies as shown in curve A of Fig. 10.

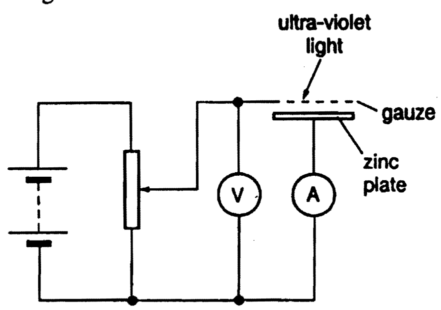


Fig. 9

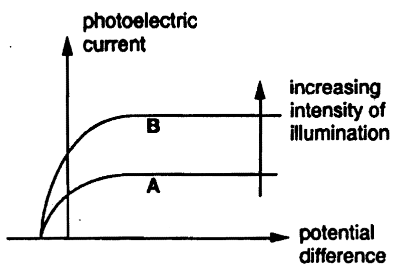


Fig. 10

(i) Explain why, for curve **A**, the photoelectric current reaches a maximum value no matter how large V is made.

(ii) The battery connections are reversed so that the potential difference V is made negative. Photo-electrons are now repelled, but some still reach the gauze. Explain why some electrons still reach the gauze. [4]

(c) The intensity of illumination is then increased and the experiment repeated to obtain curve **B** in Fig. 10.

(i) Explain why the maximum photoelectric current is increased.

(ii) Suggest why the value of V necessary to prevent any photoelectric current remains constant. [3]

N97/II/8

45 (a) Describe the phenomenon of photoelectric emission. [3]

(b) Give the meaning of the following terms, as used in describing the photoelectric effect.

(i) photon

(ii) work function energy

(iii) threshold frequency [4]

(c) Calculate the energy of a photon of light of wavelength 5.89×10^{-7} m. [3]

J2000/II/6

Long Questions

46 Explain what is meant by *photoelectric emission*.

The current from a photoemissive photoelectric cell can be reduced to zero by the appropriate application of a potential difference V when the cell is illuminated by a light of frequency ν. Sketch a graph to illustrate the variation of V with ν.

Derive a formula for V in terms of ν and other constants.

N76/III/5 (part)

47 A beacon emits millisecond flashes of green light of frequency 6.2×10^{14} Hz uniformly in all directions at one second intervals. The light power during each flash is 10 W. An observer has a telescope with an aperture of area 2.0×10^{-3} m^2. His eye-brain system perceives a flash of light when 50 or more photons are incident on a small area of his retina in less than 0.1 s.

Estimate (i) the number of photons emitted by the beacon in one millisecond, (ii) the maximum range at which the beacon might be detected by the observer using the telescope.

(The Planck constant, $h = 6.6 \times 10^{-34}$ J s.)

J80/III/2 (part)

48 What do you understand by (a) the Planck constant, h, (b) the work function, Φ, of a conductor?

Describe how h and Φ may be determined using the photoelectric effect. Indicate how the readings are processed to arrive at the required results. Explain how energy conservation is involved in the theory of the experiment.

In a photomultiplier tube, incident light ejects electrons from a cathode. These are accelerated and strike a target from which 5 electrons are ejected for every incident electron. These 5 electrons are accelerated, strike a second target so producing 25 electrons and so on. The photo multiplier tube contains a series of 9 such targets.

(i) If the electrons emitted from the final target constitute a current of 0.10 mA, calculate the rate at which photoelectrons are ejected from the cathode.

(ii) The incident light has wavelength 400 nm but, at this wavelength, only one in three of the incident photons succeeds in ejecting a photoelectron from the cathode. Calculate the light power incident on the cathode.

[The Planck constant, $h = 6.6 \times 10^{-34}$ J s.
The speed of light in vacuo, $c = 3.0 \times 10^{8}$ m s^{-1}.
The charge on the electron, $e = -1.6 \times 10^{-19}$ C.] N80/III/2

49 In a photoelectric emission experiment, ultra-violet radiation, of wavelength 254 nm and of power per unit area 210 W m^{-2}, was incident on a silver surface in an evacuated tube, so that an area of 12 mm^{2} was illuminated. A photocurrent of 4.8×10^{-10} A was collected at an adjacent electrode.

(a) What was the rate of incidence of photons on the silver surface?

(b) What was the rate of emission of electrons?

(c) The *photoelelectric quantum yield* is defined as the ratio

$$\frac{\text{number of photoelectrons emitted per second}}{\text{number of photons incident per second}}$$

(i) Find the quantum yield of this silver surface at the wavelength of 254 nm.

(ii) Give two reasons why this value might be expected to be much less than one.

(d) When the experiment was repeated with ultra-violet radiation of wavelength 313 nm, no photoelectrons were emitted. Explain this observation.

J83/I/16 (part)

50 Describe an experiment to measure the maximum energy of photoelectrons emitted from a metal. With the aid of a sketch graph, summarise the results of such experiments with light of different frequencies and with different metals. Show how a value of the Planck constant may be deduced from the results, and explain how simple wave theory fails to account for them. J84/III/2 (part)

51 A metal surface in an evacuated tube is illuminated with monochromatic light, and the photoelectrons emitted are collected at an adjacent electrode of the same metal. The photoelectric current I depends on the frequency f of the incident light, and potential difference V between collector and emitter, and the incident power P. Draw sketch graphs to show how I varies with

(i) f; V and P remaining constant,

(ii) V; P and f remaining constant,

(iii) P; f and V remaining constant.

Give an explanation, in terms of the photon theory of light, of the main features of these graphs.

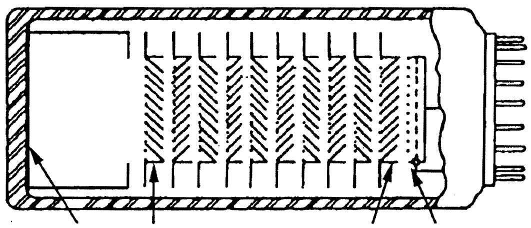


Fig. 11

A very weak beam of light may be detected using a device known as a photo-multiplier (Fig. 11). The incident light causes photoelectrons to be emitted from a cathode; these are accelerated and strike a target electrode, called the first dynode. For each electron incident, six leave the dynode. These six are accelerated to a second dynode, so producing 36 electrons, which are all accelerated to the third dynode, and so on. The photomultiplier contains a series of ten dynodes in all.

(a) If a single photoelectron arrives at the first dynode, how many electrons leave the tenth dynode?

(b) If electrons emitted from the tenth dynode are collected and constitute a current of 7.2 μA, at what rate are photoelectrons emitted from the cathode?

(c) The incident light has a wavelength of 365 nm. At this wavelength one in three of the incident photons ejects an electron from the photocathode. Find the power of the incident light. N85/II/12

52 *(a)* Place the visible, infra-red, ultra-violet and X-ray regions of the electromagnetic spectrum in order of increasing photon energy. Give a typical photon energy for visible light. [4]

N88/III/9 (part)

53 *(a)* What is the *photoelectric effect*? Outline how this effect may be demonstrated experimentally. [5]

(b) In one demonstration, photoelectrons are being produced at a rate of 2.7×10^{13} per second. Assume each electron has an energy of 1.2×10^{-19} J.

(i) Calculate the current giving this rate of pro-duction of photoelectrons.

(ii) Define *electromotive force* (e.m.f.) and hence determine the e.m.f. generated. [5]

(c) State, with a reason, what modifications to the apparatus of the demonstration which you have outlined in *(a)* would be required, separately, to increase

(i) the energy of a photoelectron,

(ii) the rate of production of photoelectrons. [4]

(d) What does the photoelectric effect demonstrate about the nature of electromagnetic radiation? In what way does diffraction of light give rise to a theory which is inconsistent with the evidence shown by the photoelectric effect? [3]

(e) Describe how the evidence provided by experiments to show the wave nature of electrons enabled the apparent inconsistency in *(d)* to be explained. [3] N92/III/6

54 *(a)* Describe a laboratory demonstration which cannot be explained by the wave theory of light but which requires an explanation in which light has a particulate nature. [4]

(b) For light of wavelength 5.62×10^{-7} m, calculate

(i) its frequency,

(ii) the energy of a photon,

(iii) the rate of emission of photons for a light power of 18.7 W. [6]

J93/III/6 (part)

55 *(b)* (i) State what is meant by the *photoelectric effect.*

(ii) Give **three** of the experimental observations associated with this effect. [5]

(c) (i) A lamp is placed above a metal surface which contains atoms of radius 2.0×10^{-10} m. Each electron in the metal requires a minimum energy of 3.2×10^{-19} J before it can be emitted from the metal surface, and it may be assumed that the electron can collect energy from a circular area which has a radius equal to that of the atom. The lamp provides energy at a rate of 0.40 W m^{-2} at the metal surface.

Estimate, on the basis of wave theory, the time required for an electron to collect sufficient energy for it to be emitted from the metal.

(ii) Comment on your answer to *(c)*(i). [5]

J94/III/5 (part)

56 *(a)* Give an expression for E, the energy of a photon, in terms of f, its frequency, and h, the Planck constant. [1]

(b) State a wavelength within the visible spectrum and, for that wavelength, calculate the energy of a photon. [3]

(c) Wave theory predicts that, if electromagnetic radiation strikes a metal surface and ejects an electron, the kinetic energy of the electron should depend on the intensity of the wave. Observation shows that, in its interaction with matter to release an electron, it is the frequency of the electromagnetic wave, and not the intensity, which controls the maximum kinetic energy of the electron.

(i) What is the name given to the effect of using electromagnetic radiation to cause an electron to be emitted from a metal surface?

(ii) Explain how this effect gave evidence for the particulate nature of electromagnetic radiation in its interaction with matter.

(iii) What is meant by the term *threshold frequency* for the wave? [6]

(d) Figure 12 is a graph showing the maximum kinetic energies, in electron volts, of electrons emitted from a sodium surface by light of different frequencies from a hydrogen light source.

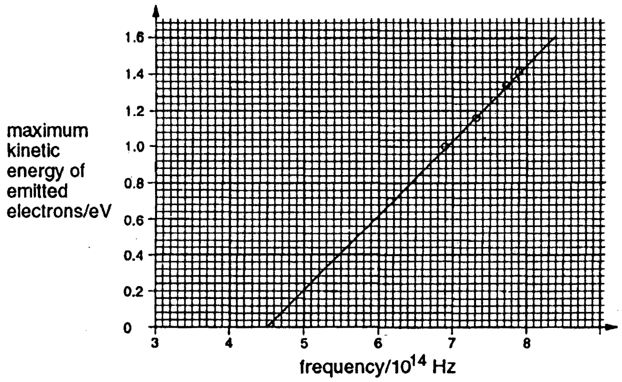


Fig. 12

(i) What energy is 1 electron volt (1 eV) when expressed in joules? [1]

(ii) What is the threshold frequency for sodium? [1]

(iii) Calculate the work function energy, in joules, for sodium. [2]

(iv) In calculations on electron emission, an equation which is often used is

photon energy = work function energy + maximum kinetic energy of the emitted electrons

With the help of the graph, state the numerical values for these three terms when the incident radiation from the hydrogen lamp has a frequency of 6.2×10^{14} Hz. [3]

(e) The frequencies of light from the lamp, shown by the small circles on the graph in Fig. 12, are the only frequencies obtained in this range. Explain how this shows the existence of discrete energy levels in hydrogen atoms. Without giving numerical values, sketch the pattern of these levels. [3]

N94/III/6

57 *(a)* (i) Describe the photoelectric effect. [3]

(ii) Explain how the photoelectric effect provides evidence for a particulate nature of electromagnetic radiation. [4]

(b) The graph drawn in Fig. 13 shows how the maximum kinetic energy E_k of a photoelectron from a particular material varies with the frequency f of the electromagnetic radiation that causes the emission of photoelectrons.

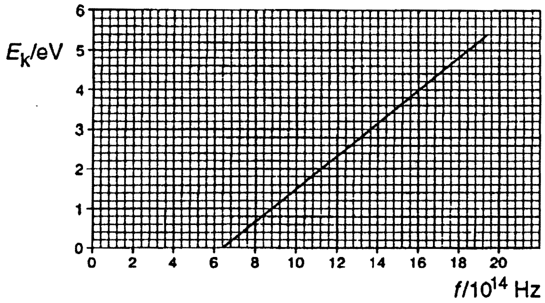


Fig. 13

(i) Use the graph to determine

1. the threshold frequency for this material,
2. the maximum kinetic energy of photo-electrons from this material when it is illuminated with electromagnetic radiation of frequency 18.0×10^{14} Hz. Give your answer in joules. [4]

(ii) Use the photoelectric equation and your answers from (i) to determine the Planck constant. [3]

N2000/III/6 (part)

Wave-Particle Duality

58 Light of frequency 5×10^{14} Hz consists of photons of momentum

A 4.0×10^{-40} kg m s^{-1}
B 3.7×10^{-36} kg m s^{-1}
C 1.7×10^{-28} kg m s^{-1}
D 1.1×10^{-27} kg m s^{-1}
E 3.3×10^{-19} kg m s^{-1}

J76/II/13

59 The de Broglie wavelength of a rifle bullet of mass 0.02 kg which is moving at a speed of 300 m s^{-1} is

A 7.3×10^{-36} m
B 1.8×10^{-35} m
C 1.1×10^{-34} m
D 9.9×10^{33} m
E 1.4×10^{35} m

[The Planck constant, $h = 6.6 \times 10^{-34}$ J s.]

J77/II/33

60 The wave nature of electrons is suggested by experiments on

A line spectra of atoms.
B the production of X-rays.
C the photoelectric effect.
D electron diffraction by a crystalline material.
E β-decay of nuclei.

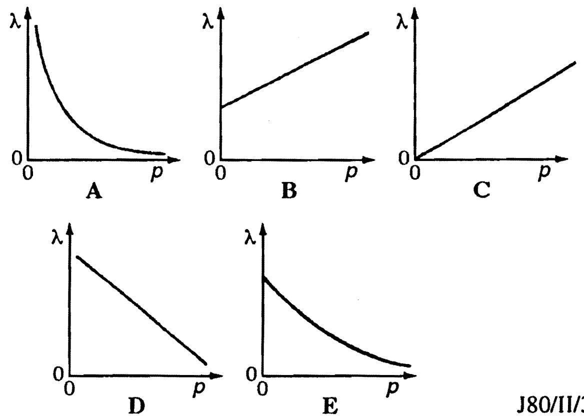
N79/II/33

61 Smaller objects may be distinguished in electron microscopes than in optical microscopes because

A electrons are smaller than visible quanta.
B the electrons travel much faster than light.
C there is no chromatic aberration with electrons.
D the electron wavelength is much shorter than that of visible light.
E the electrons are not diffracted.

N79/II/39

62 In 1923, de Broglie suggested that an electron of momentum p has properties corresponding to a wave of wavelength λ. Which one of the following graphs correctly shows the relationship between λ and p?



J80/II/37

63 A beam of light of wavelength λ is totally reflected at normal incidence by a plane mirror. The intensity of the light is such that photons hit the mirror at a rate n. Given that the Planck constant is h, the force exerted on the mirror by this beam is

A $nh\lambda$
B nh/λ
C $2nh\lambda$
D $2n\lambda/h$
E $2nh/\lambda$

N80/II/15

64 If the de Broglie waves associated with each of the following particles are to have the same wavelength, which particle must have the smallest velocity?

A proton
B α-particle
C ${}^{2}_{1}$H nucleus (deuteron)
D electron
E neutron

N81/II/35

65 What is the de Broglie wavelength of a particle of mass m and kinetic energy E?

[h is the Planck constant.]

A $h\sqrt{(2mE)}$
B $\sqrt{(2mE)}\,/\,h$
C $h\,/\sqrt{(mE)}$
D $h\,/\sqrt{(2mE)}$
E $h\sqrt{2}\,/\sqrt{(mE)}$

N82/II/33

66 The intensity of a beam of monochromatic light is doubled. Which one of the following represents the corresponding change, if any, in the momentum of each photon of the radiation?

A increased fourfold
B doubled
C the same
D halved
E reduced fourfold

J83/II/34

67 An electron has mass m_e and speed 0.02 c, where c is the speed of light in free space.

What is the de Broglie wavelength of this electron, expressed in terms of the Planck constant h?

A $\dfrac{h}{(0.02c)}$ C $\dfrac{h}{(0.02c)m_e}$

B $\dfrac{(0.02c)}{h}$ D $\dfrac{(0.02c)m_e}{h}$ J2000/I/28

68 Electrons are accelerated from rest by a p.d. of 1000 V in a vacuum. After passing through a very thin crystal, many are observed to emerge with a deflection of 5°. If the accelerating potential is now doubled

(a) calculate the ratio of the new electron speed to the old,

(b) calculate the wavelength associated with the electrons at the higher speed.

(c) what new angle of deflection corresponds to the wavelength in *(b)*?

[Electron charge = -1.6×10^{-19} C; electron mass = 9.1×10^{-31} kg; the Planck constant = 6.6×10^{-34} J s.]

N76/I/4

69 Find *(a)* the energy, *(b)* the momentum, of photons of light of wavelength 500 nm.

[Speed of light, $c = 3.0 \times 10^8$ m s^{-1}; the Planck constant, $h = 6.6 \times 10^{-34}$ J s.]

J77/I/2

70 What information can be deduced about the nature of *(a)* crystalline solids, *(b)* electrons, from the experimental observation that electrons of suitable energies are strongly scattered in certain directions by crystals? Make an estimate of the minimum energy of the electrons for them to be diffracted in this way, showing how you arrive at your answer.

[Take the Planck constant h as 7×10^{-34} J s and the mass of the electron m_e as 1×10^{-30} kg.]

N78/I/11

71 Find an expression for the de Broglie wavelength of an electron in terms of its kinetic energy E, the electron mass m_e, and the Planck constant h.

J79/I/11

72 Electromagnetic waves consist of transverse, sinusoidally-varying, electric and magnetic field components, perpendicular to each other and to the direction of propagation. The speed of propagation in vacuum is constant for electro-magnetic waves of all wavelengths.

A beam of electrons has an associated wave property. Because it consists of a stream of moving electric charges, it also produces a magnetic field. The beam can pass through a vacuum. Discuss very briefly whether, on the basis of these experimental facts, electron beams could be classified as electromagnetic waves. J84/I/6

73 Electron diffraction experiments show that the wavelength associated with a certain electron beam is 0.15 nm. Find the momentum of an electron in the beam. Through what potential difference should the electrons be accelerated from rest to acquire this momentum? N84/I/10

74 Under certain conditions, electrons show wave-like properties. Find the wavelength of an electron of kinetic energy 1×10^{-18} J.

This energy is typical of electrons in atoms. Comment on the wavelength you have calculated in relation to the size of an atom. N85/II/7

75 Evidence for the wave nature of the electron comes from experiments in which an electron beam is diffracted by the atoms in a crystalline solid.

(a) Write down an approximate value for the separation of neighbouring atoms in a typical crystalline solid.

(b) If the electron wavelength is comparable with this interatomic separation, estimate the momentum of an electron in the beam. [3] N87/II/7

76 A parallel beam of violet light of wavelength 4.5×10^{-7} m and intensity 700 W m^{-2} is incident normally on a surface.

(a) Calculate

(i) the energy of a photon of violet light,

energy = ... J

(ii) the number of photons incident per second on 1.0×10^{-4} m^2 of the surface.

number = ...[3]

(b) (i) State the de Broglie relation for the momentum p of a particle in terms of its associated wavelength λ.

(ii) Use the equation in (i) to calculate the momentum of a photon of the violet light.

momentum = ...Ns[2]

(c) (i) Use your answers to *(a)* and *(b)* to calculate the change in momentum of photons incident on 1.0×10^{-4} m^2 of the surface in one second. Assume that the photons are absorbed by the surface.

change in momentum = ...N s

(ii) Suggest why the quantity you have calculated in (i) is referred to as a 'radiation pressure'. [3]

N98/II/7

Long Questions

77 Electrons injected at right angles into a magnetic field of flux density 0.1 T follow circular paths of radius 2×10^{-3} m. Explain how this happens and calculate the wavelength associated with such electrons. [8]

[electronic charge, $e = -1.6 \times 10^{-19}$ C;
the Planck constant, $h = 6.6 \times 10^{-34}$ J s.] N77/III/5 (part)

78 Outline an experiment to demonstrate the phenomenon of electron diffraction. Summarise the results of such experiments with electrons of various speeds. State the de Broglie relationship, and explain how simple particle theory fails to account for this relationship.

A certain electron stream and an X-ray beam produce identical diffraction patterns when they interact with the same object. Deduce an expression for the potential difference V required to accelerate the electrons from rest in terms of the wavelength of the X-ray beam, the charge and mass of the electron, and the Planck constant.

J84/III/2 (part)

79 Draw a labelled diagram of an apparatus which may be used to demonstrate the phenomenon of electron diffraction.

Sketch a typical diffraction pattern obtained in this experiment, and explain qualitatively why it has this form.

Explain very briefly the significance of this experiment.

Two large plane metal electrodes are arranged parallel to each other in an evacuated tube. One (the collector) is at a positive potential with respect to the other (the emitter). Starting from rest, an electron leaves the middle of the emitter and moves perpendicularly to the plates towards the collector. Sketch clearly-labelled graphs showing how the following quantities depend on the distance x from the emitter:

(a) the electric potential energy E_p of the electron,

(b) its kinetic energy E_k,

(c) its speed v,

(d) its associated wavelength λ.

If the accelerating potential is 150 V, find the wavelength associated with the electron as it reaches the collector.

J86/II/12

80 *(a)* Outline and explain experimental observations, one in each case, which provide evidence for the following statements:

(i) Light is a wave motion.

(ii) Light consists of photons having some of the properties of particles.

(iii) Electrons are particles.

(iv) A beam of electrons has wave properties. [16]

(b) Observations such as those listed in *(a)* have led to the idea of wave-particle duality.

(i) Explain what is meant by the term wave-particle duality.

(ii) Why is it that sound waves are not normally considered as having particle-like properties, nor raindrops as having wave-like properties? [6]

J89/II/12

81 *(c)* (i) Electromagnetic waves have a wave nature as well as a particulate nature. This is known as wave/particle duality. Describe a situation in which particles can be shown to have a wave nature. [3]

(ii) Calculate the wavelength of a particle of mass 1.82×10^{-28} kg when travelling with a speed equal to 10% of the speed of light. [3]

N2000/III/6 (part)