PHYSICS

BOOKS - VIKRAM PUBLICATION (ANDHRA PUBLICATION)

DUAL NATURE OF RADIATION AND MATTER

Sample Problem

1. Calculate the (a)momentum and (b) de - Brogile wavelength of the electrons accelerated through a potential difference of 56 V.

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2. The work function of caesium is 2.14 eV. When light of frequency $6 \times 10^{14} Hz$ is incident on the metal surface, photoemission of electrons occurs. What is the (a) maximum kinetic energy of the emitted electrons. (b) stopping potential and (c) maximum speed of the emitted photoelectrons. given , $h = 6.63 \times 10^{-34} Js, 1eV = 1.6 \times 10^{-19} J, c = 3 \times 10^{8} m/s.$

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Textual Examples

1. Monochromatic light of frequency 6.0×10^{14} Hz is produced by a laser. The power emitted is 2.0×10^{-3} W(a) What is the energy of a photon in the light beam ? (b) How many photons per second , on an average , are emitted by the source ?

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2. The work function of caesium is 2.14 eV . Find (a) the threshold frequency for caesium , and (b) the wavelength of the incident light if the photocurrent is brought to zero by a stopping potential of 0.60 V.

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3. The wavelength of light in the visible region is about 390 nm for violet colour, about 550 nm (average wavelength) for yellow - green colour and about 760 nm for red colour .

(a) What are the energies of photons in (ev) at the (i) violet end, (ii) average wavelength , yellow - green colour , and (ii) red end of the visible spectrum ? (Take h = 6.63×10^{-34} J s and 1 eV= 1.6×10^{-19} J) ,

Metal	Work function ϕ_0 (eV)	Metal	Work function ϕ_0 (eV)
Cs	2.14	Al	4.28
K	2.30	Hg	4.49
Na	2.75	Cu	4.65
Ca	3.20	Ag	4.70
Mo	4.17	Ni	5.15
Pb	4.25	Pt	5.65

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4. The wavelength of light in the visible region is about 390 nm for violet colour, about 550 nm (average wavelength) for yellow - green colour and about 760 nm for red colour .

From which of the photosensitive materials with work functions listed in table and using the results of (i) , (ii) and (iii) of (a) can you build a photoelectric device that operates with visible light ?

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5. What is the de-Broglie wavelength associated with (a) an electron moving with speed of $5.4 \times 10^6 ms^{-1}$, and (b) a ball of mass 150g traveling at $30.0ms^{-1}$? $h = 6.63 \times 10^{-34} Js$, mass of electron $= 9.11 \times 10^{-31} kg$.

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6. An electron, an α-particle, and a photon have the same kinetic energy. Which of these particles has the shortest, de -broglie wavelenght?

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7. A particle is moving three times as fast as an electron. The ratio of the de- Broglie wavelength of the particle to that of the electron is 1.813×10^{-4}. Calculate the particle's mass and identify the particle. Mass of electron $= 9.11 \times 10^{-31} kg$.

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8. What is the de Broglie wavelength associated with an electron , accelerated through a potential difference of 100 volts ?

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Very Short Answer Questions

1. What are cathode rays ?

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2. What important fact did Millikan's experiment establish ?

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3. What is "work function "?

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4. Photoelectric effect

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5. Give examples of " photosensitive substances " . Why are they called so ?

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6. Write down Einstein's photoelectric equation .

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7. Write down de - Broglie's relation and explain the terms there in .

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8. State Heisenberg's Uncertainity Principle

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Short Answer Questions

1. What is the effect of (i) intensity of light (ii) potential on photoelectric current ?

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2. Describe an experiment to study the effect of frequency of incident radiation on 'stopping potential ' .

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3. Summarise the photon picture of electromagnetic radiation .

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4. What is the de Broglie wavelength of a ball of mass 0.12 Kg moving with a speed of 20 ms^{-1} ? What can we infer from this result ?

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Long Answer Questions

1. How did Einstein's photoelectric equation explain the effect of intensity and potential incident on photoelectric current ? How did this eqaution account for the effect of frequency of incident light on stopping potential ?

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2. Describe the Davisson and Germer experiment . What did this experiment conclusively prove ?

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Textual Exercises

1. Find the

(a) maximum frequency, and

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2. Find the and

minimum wavelength of X-rays produced by 30 kV electrons .

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3. The work function of caesium metal is 2.14 eV . When light of frequency 6×10^{14} Hz is incident on the metal surface , photomission of electrons occurs . What is the

maximum kinetic energy of the emitted electrons

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4. The work function of caesium metal is 2.14 eV . When light of frequency 6×10^{14} Hz is incident on the metal surface , photomission of electrons occurs . What is the

stopping potential and

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5. The work function of caesium metal is 2.14 eV . When light of frequency 6×10^{14} Hz is incident on the metal surface , photomission of electrons occurs . What is the

maximum speed of the emitted photoelectrons ?

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6. The photoelectric cut-off voltage in certain experiment is 1.5 V. What is the maximum kinetic energy of photoelectrons emitted ?

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7. Monochromatic light of wavelength 632.8 nm is produced by a helium-neon laser. The power emitted is 9.42 mW.

Find the energy and momentum of each photon in the light beam,

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8. Monochromatic light of wavelength 632.8 nm is produced by a helium-neon laser. The power emitted is 9.42 mW.

How many photons per second, on the average, arrive at a target irradiated by this beam ? (Assume the beam to have uniform cross-section which is less than the target area),

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9. Monochromatic light of wavelength 632.8 nm is produced by a helium-neon laser. The power emitted is 9.42 mW.

How fast does a hydrogen atom have to travel in order to have to have the same momentum as that of the photon ?

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10. The energy flux of sunlight reaching the surface of the earth is $1.388 \times 10^3 \mathrm{W/m^2}$. How many photons (nearly) per square metre are incident on the Earth per second ? Assume that the photons in the sunlight have an average wavelength of 550 nm.

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11. In an experiment on photoelectric effect , the slope of the cut - off voltage versus frequency of incident light is found to be 4.12×10^{-15} V s . Calculate the value of Planck's constant.

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12. A 100 W sodium lamp radiates energy uniformly in all directions. The lamp is located at the centre of a large sphere that absorbs all the sodium light which is incident on it. The wavelength of the sodium light is 589 nm.

What is the energy per photon associated with the sodium light ?

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13. A 100 W sodium lamp radiates radiates energy uniformly in all directions. The lamp is located at the centre of a large sphere that absorbs all the sodium light which is incident on it. The wavelength of the sodium light is 589 nm.

At what rate are the photons delivered to the sphere ?

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14. The threshold frequency for a certain metal is 3.3×10^{14} Hz. If light of frequency 8.2×10^{14} Hz is incident on the metal, predict the cut-off voltage for the photoelectric emission.

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15. The work function for a certain metal is 4.2 eV. Will this metal give photoelectric emission for incident radiation of wavelength 330 nm ?

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16. Light of frequency 7.21×10^{14} Hz is incident on metal surface. Electrons with a maximum speed of $6.0 \times 10^{5} m/s$ are ejected from the surface. What is the threshold frequency for photoemission of electrons ?

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17. Light of wavelength 488 nm is produced by an argon laser which is used in the photoelectric effect. When light from this spectral line is incident on the emitter, the stopping (cut - off) potential of photoelectrons is 0.38 V. Find the work function of the material from which the emitter is made.

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18. Calculate the

Momentum,

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19. Calculate the

de Broglie wavelength of the electrons accelerated through a potential

difference of 56 V.

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20. What is the

momentum

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21. What is the

Speed

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22. What is the

Be Broglie wavelength of an electron with kinetic energy of 120 eV.

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23. The wavelength of light from the spectral emission line of sodium is

589 nm. Find the kinetic energy at which

(i) an electron, and

(ii) a neutron, would have the same de-Broglie wavelength .

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24. The wavelength of light from the spectral emission line of sodium is

589 nm. Find the kinetic energy at which

A neutron, and would have the same de Broglie wavelength.

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25. What is the de-Broglie wavelength of (a) a bullet of mass $0.040kg$ traveling at the speed of $1.0kms^{-1}$. (b) a ball of mass $0.060kg$ moving at a speed of $1.0ms^{-1}$ and (c) a dust particle of mass $1.0 \times 10^{-9}kg$ drifting with a speed of $2.2ms^{-1}$? $h = 6.63 \times 10^{-34}Js$.

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26. What is the de-Broglie wavelength of (a) a bullet of mass $0.040kg$ traveling at the speed of $1.0kms^{-1}$. (b) a ball of mass $0.060kg$ moving at a speed of $1.0ms^{-1}$ and (c) a dust particle of mass $1.0 \times 10^{-9}kg$ drifting with a speed of $2.2ms^{-1}$? $h = 6.63 \times 10^{-34}Js$.

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27. What is the de Broglie wavelength of

A dust particle of mass 1.0×10^{-9} kg drifting with a speed of 2.2 m/s ?

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28. An electron and a photon each have a wavelength 1.00 nm. Find

(i) their momenta,

(ii) the energy of the photon and

(iii) the kinetic energy of electron.

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29. An electron and a photon each have a wavelength 1.00 nm. Find

(i) their momenta,

(ii) the energy of the photon and

(iii) the kinetic energy of electron.

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30. An electron and a photon each have a wavelength 1.00 nm. Find

(i) their momenta,

(ii) the energy of the photon and

(iii) the kinetic energy of electron.

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31. For what kinetic energy of a neutron will the associated de-Broglie wavelength be $1.40 \times 10^{-10} m$? Mass of neutron = $1.675 \times 10^{-27} kg, h = 6.63 \times 10^{-34} Js.$

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32. A. For what kinetic energy of neutron will the associated de Broglie wavelength be $1.40 \times 10^{-10} m?$

B. Also, find the de Broglie wavelength of a neutron, in thermal equilibrium with matter, having an average kinetic energy of $\left(\frac{3}{2}\right)$ kT at $300K$. Given the mass of neutron $= 1:66 \times 10^{-27} kg$ and $k = 1.38 \times 10^{-23} Jkg^{-1}$`.

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33. Show that the wavelength of electromagnetic radiation is equal to the de-Broglie wavelength of its quantum (photon).

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34. What is the de-Broglie wavelength of nitrogen molecule in air at 300K ? Assume that the molecule is moving with the root mean square speed of molecules at this temperature. (Atomic mass of nitrogen $= 14.0076U$) Plank's constant=$6.63 \times 10^{-34} Js$, Boltzmann constant $= 1.38 \times 10^{-23} JK^{-1}$

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Additional Exercises

1. (a) Estimate the speed with which electrons emitted from a heated cathode of an evacuated tube impinge on the anode maintained at a potential difference of 500 V with respect to the cathode. Ignore the small initial speeds of the electrons. The specific charge to of the electron, i.e., its e/m is given to $1.76 \times 10^{11} Ckg^{-1}$.

(b) Use the same formula you employ in (a) to obtain electron speed for an anode potential of 10 MV. Do you see what is wrong? In what way is the formula to be modified?

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2. Use the same formula you employ in (a) to obtain electron speed for an collector potential of 10 MV. Do you see what is wrong ? In what way is the formula to be modified ?

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3. A monoenergetic electron beam with electron speed of $5.20 \times 10^6 \mathrm{m\ s}^{-1}$ is subject to a magnetic field of 1.30×10^{-4} T normal to the beam velocity . What is the radius of the circle traced by the beam , given e/m for electron equals $1.76 \times 10^{11}\ \mathrm{C\,kg}^{-1}$

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4. Is the formula you employ in (a) valid for calculating radius of the path of a 20 MeV electron beam ? If not , in what way is it modified ? ,

[Note : Exercises 20 (b) and (21) b take you to relativistic mechanics which is beyond the scope of this book . They have been inserted here simply to emphasise the point that the formulas you use in part (a) of the exercises are not valid at very high speeds or energies . See answers at the end to know what very high speed or energy means .]

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5. An electron gun with its collector at a potential of 100 V fires out electrons in a spherical bulb containing hydrogen gas at low pressure (~10^{-2} mm of Hg). A magnetic field of 2.83×10^{-4} curves the path of the electrons in a circular orbit of radius 12.0 cm . (The path can be viewe because the gas ions in the path focus the beam by attracting electrons and emitting light by electron capture , the method is known as the 'fine beam tube ' method) Determine e/m from the data .

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6. An X - ray tube produces a continous spectrum of radiation with its short wavelength end at 0.45 Å . What is the maximum energy of a photon in the radiation?

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7. From your answer to (a) , guess what order of accelerating voltage (for electrons) is required in such a tube ?

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8. In an accelerator experiment on high energy collision of electrons with positrons, a certain events is interpreted as annihilation of an electron-positron pair of total energy 10.2 BeV into two γ-rays of equal energy. What is the wavelength associated with each γ-rays? $(1BeV = 10^9 eV)$

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9. Estimate the following the following two numbers should be interesting. The first number will tell you why radio engineers do not need to worry much about a photons. The second number tells you why our eye can never "count photon" even in barely detectable light.

(i) The number of photons emitted per second by a MW transmitter of 10kW power emitting radiowaves of length 500m.

(ii) The number of photons entering the pupil of our eye per second corresponding to the minimum intensity of white light that we humans can perceive $(\text{~}10^{-10} Wm^{-2})$. Take the area of the pupil to be about $0.4cm^2$, and the average frequency of white light to be about $6 \times 10^4 Hz$. $(h = 6.6 \times 10^{-34} J)$

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11. Ultraviolet light of wavelength $2271Å$ from a 100W mercury source irradiates a photocell made of molybdenum metal. If the stopping potential is 1.3V, estimate the work function of the metal. How would the photocell respond to a high intensity $(\text{~}10^5 Wm^{-2})$ red light of wave length $6328Å$ produced by a He-Ne laser?

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12. Monochromatic radiation of wave length 640.2 nm $(1nm = 10^{-9} m)$ from a neon lamp irradiates a photosensitive material made of calcium or tungsten. The stopping voltage is measured to be 0.54V. The source is replaced by an iron source and its

427.2 nm line irradiates the same photocell. Predict the new stopping voltage.

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13. A mercury lamp is a convenient source for studying frequency dependence of photoelectric emission, since it gives a number of spectral lines ranging from the UV to the end of the red visible spectrum. In our experiment with rubidium photocell, the following lines from a mercury source were used: $\lambda_1 = 3650A^\circ, \lambda_2 = 4047A^\circ, \lambda_3 = 4358A^\circ, \lambda_4 = 5461A^\circ, \lambda_5 = 6907A^\circ$

The stopping voltages, respectively were measured to be:

$V_{01} = 1.28V, V_{02} = 0.95V, V_{03} = 0.74V, V_{04} = 0.16V, V_{05} = 0V.$

(a) Determine the value of Planck's constant h.

(b) Estimate the threshold frequency and work function for the material.

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14. The work function for the following metals is given Na: 2.75 eV, K:2.30 eV , Mo: 4.17 eV , Ni: 515 eV.

Which of these metals will not give photoelectric emission for a radiation of wavelength 3300 A from a $He - Cd$ laser placed 1m away from the photocell? What happens if the laser is brought nearer and placed 50 cm away?

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15. Light of intensity $10^{-5} Wm^{-2}$ falls on a sodium photocell of surface area $2cm^2$. Assuming that the top 5 layers of sodium absorb the incident energy, estimate the time required for photoelectric emission in the wave picture of radiation. The work function of the metal is given to be about 2eV. What is the implication of your answer? effective atomic area $= 10^{-20} m^2$.

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16. Crystal diffraction experiments can be performed using X-rays, or electrons accelerated through appropriate voltage. Which probe has greater energy? An X-ray photon or the electron? (For quantitative comparison, take the wavelength of the probe equal to 1Å, which is of the order of interatomic spacing in the lattice), $m_e = 9.11 \times 10^{-31} kg$.

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17. (a) Obtain the de-Broglie wavelength of a neutron of kinetic energy 150 eV. As you have seen in previous problem 31, an electron beam of this energy is suitable for crystal diffraction experiments. Would a neutron beam of the same energy be equally suitable? Explain. Given $m_n = 1.675 \times 10^{-27} kg$.

(b) Obtain the de-Broglie wavelength associated with thermal neutrons at room temperature $(27^\circ C)$. Hence explain why a fast neutrons beam needs to be thermalised with the environment before it can be used for neutron diffraction experiments.

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19. An electron microscope uses electrons accelerated by a voltage of $50kV$. Determine the De Broglie wavelength associated with the electrons. If other factors (such as numerical aperture, etc.) are taken to be roughly the same, how does the resolving power of an electron microscope compare with that of an optical microscope which uses yellow light?

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20. The wavelength of a probe is roughly a measure of the size of structure that it can probe in some detail. The quarks structure of photons and neutrons appears at the minute length -scale of $10^{-15}m$ or less. This structure was first probed in early 1970's using high energy electron beam produced by a linear accelerator at Stanford's USA. Guess what might have been the order of energy of these electron beams (Rest mass energy of electron=0.511 eV).

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21. Find the typical de-Broglie wavelength associated with a H-atom in helium gas at room temperature $(27^{\circ} C)$ and 1atm pressure, and compare it with the mean separation between two atom under these conditions.

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22. Compute the typical de-Broglie wavelength of an electrons in a metal at $27^{\circ} C$ and compare it with the mean separation between two electrons in a metal which is given to be about $2 \times 10^{-10} m$.

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23. Answer the following questions:

(a) Quarks inside protons and neutrons are thought to carryfractional charges [(+2/3)e , (–1/3)e]. Why do they not show up in Millikan's oil-drop experiment?

(b) What is so special about the combination e/m? Why do we not simply talk of e and m separately?

(c) Why should gases be insulators at ordinary pressures and start conducting at very low pressures?

(d) Every metal has a definite work function. Why do all photoelectrons not come out with the same energy if incident radiation is monochromatic? Why is there an energy distribution of photoelectrons?

(e) The energy and momentum of an electron are related to the frequency and wavelength of the associated matter wave by the relations:

$E = h\nu, p = \frac{\lambda}{h}$

But while the value of λ is physically significant, the value of ν (and therefore, the value of the phase speed ν λ) has no physical significance. Why?

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24. What is so special about the combination e/m ? Why do we not simply talk of e and m separately ?

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25. Why should gases be insulators at ordanary pressures and start conducting at very low pressures ?

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27. The energy and momentum of an electron are related to the frequency and wavelength of the associated matter wave by the relations :

$$E = hv, p = \frac{h}{\lambda}$$

But while the value of λ is physically signidficant , the value of v (and therefore , the value of the phase speed v λ) has no physical significance . Why ?

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1. The wavelength of electromagnetic radiation is doubled. What will happen to the energy of the photons of the new radiation ?

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2. Show that the wavelength of electromagnetic radiation is equal to the de-Broglie wavelength of its quantum (photon).

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