Questions

Module 7: The Nature of Light

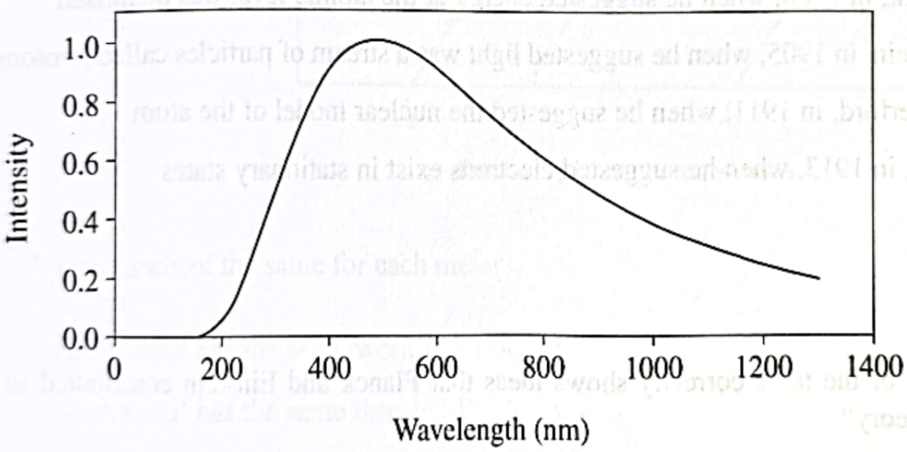
7.3 Light: Quantum Model

Multiple-choice questions: 1 mark each

Note: In the past, HSC questions used other notations for kinetic energy, e.g. KE, E_k

These have not always been changed to the current notation, K, in the past HSC questions here – as these different notations are still commonly used and so students should be familiar with them.

1. The graph shows the intensity–wavelength relationship of electromagnetic radiation emitted from a black body cavity.



In 1900, Planck proposed a mathematical formula that predicted an intensity–wavelength relationship consistent with the experimental data.

The success of this formula depended on which of the following hypotheses?

(A) The intensity of light is dependent on the wavelength.

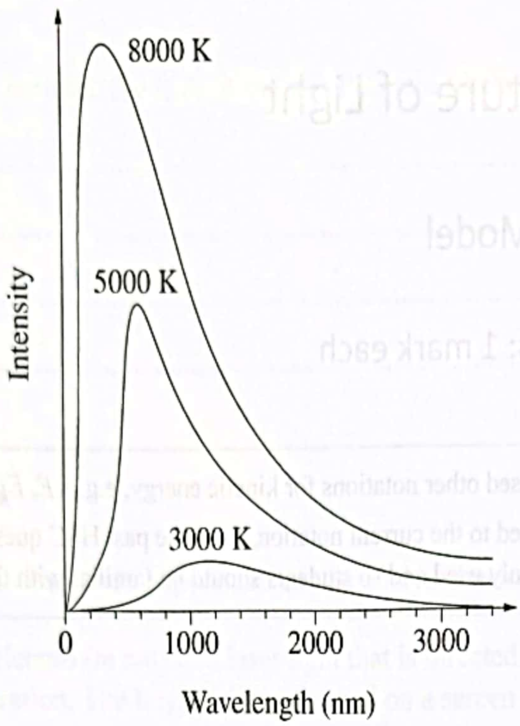
(B) Light is quantised, with the energy of light quanta depending on the frequency.

(C) Light is a wave whose intensity is readily expressed using mathematical formulae.

(D) Light is quantised, with the energy of the light quanta depending on the size of the cavity from which it is emitted.

2004 HSC Q15

2. The family of curves below shows the relationship between the intensity of black body radiation and its wavelength for various Kelvin temperatures.



Who was the first to correctly explain this relationship?

(A) Planck, in 1900, when he suggested energy at the atomic level was quantised

(B) Einstein, in 1905, when he suggested light was a stream of particles called photons

(C) Rutherford, in 1911, when he suggested the nuclear model of the atom

(D) Bohr, in 1913, when he suggested electrons exist in stationary states

2005 HSC Q12

3. Which row of the table correctly shows ideas that Planck and Einstein contributed to quantum theory?

	Planck	*Einstein*
(A)	Hot objects emit radiation in discrete amounts.	Light consists of packets of energy with specific values.
(B)	Planck's constant determines the energy of photons.	Objects emit energy that increases exponentially with frequency.
(C)	No energy is lost from black body radiators.	Energy is absorbed if the band gap is less than the photon energy.
(D)	The energy of photons decreases as the wavelength increases.	Photons have energy proportional to their frequency.

2015 HSC Q17

4. Why is there low intensity of black body radiation at very short wavelengths?

(A) The energy of each photon is reduced at very short wavelengths.

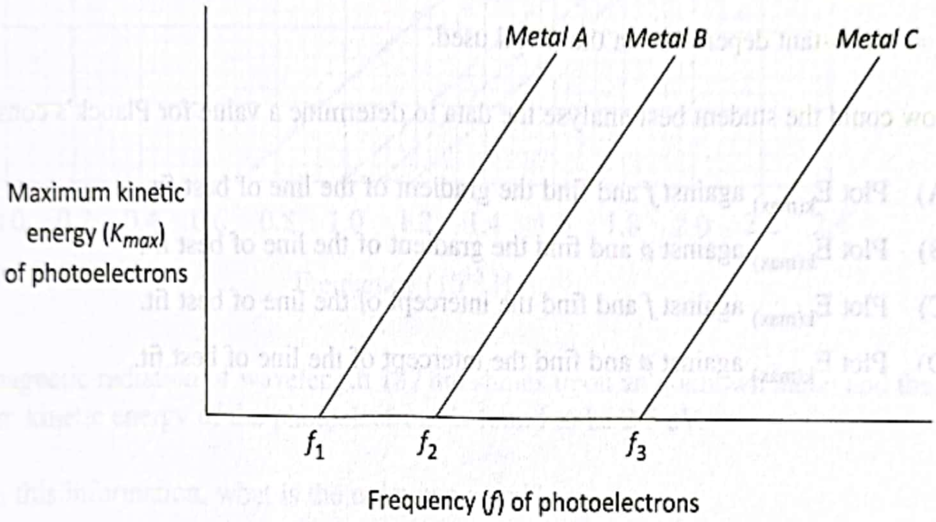
(B) There are fewer photons with high energy at very short wavelengths.

(C) Only photons of very short wavelengths are reabsorbed by the black body.

(D) Photons of very short wavelengths interact with each other causing destructive interference.

2014 HSC Q11

5. This graph shows the maximum kinetic energy with which photoelectrons are emitted versus the frequency of light (f), for three different metals A, B and C.



Why is the gradient the same for each metal?

(A) Each metal has the same work function.

(B) Each metal has the same threshold frequency.

(C) The gradient of the graph for each metal is Planck's constant.

(D) Each metal releases a photoelectron with the same kinetic energy.

6. Which of the following statements about the photoelectric effect is incorrect?

(A) When the frequency of the incident light is less than the threshold frequency, no electrons are released.

(B) The work function of a metal is the energy needed to release one electron from the surface of the metal.

(C) The maximum kinetic energy of the photoelectrons emitted from a metal is the energy of the photons minus the work function.

(D) If the frequency of the incident light is the same as the threshold frequency, then a photoelectron will be ejected.

7. A student carried out an experiment during which light of different frequencies was shone onto a metal surface to produce photoelectrons.

The student measured the maximum kinetic energy of the emitted photoelectrons as the frequency of light was altered.

The relationship between the maximum kinetic energy of the photoelectrons and the frequency of the light incident on the metal surface is given by:

$$E_{k(max)} = hf - \phi$$

where

$E_{k(max)}$ = maximum kinetic energy of the photoelectrons

f = frequency of light used

h = Planck's constant

ϕ = a constant dependent on the metal used.

How could the student best analyse the data to determine a value for Planck's constant?

(A) Plot $E_{k(max)}$ against f and find the gradient of the line of best fit.

(B) Plot $E_{k(max)}$ against ϕ and find the gradient of the line of best fit.

(C) Plot $E_{k(max)}$ against f and find the intercept of the line of best fit.

(D) Plot $E_{k(max)}$ against ϕ and find the intercept of the line of best fit.

2002 HSC Q15

8. The minimum amount of energy needed to eject an electron from a clean aluminium surface is 6.72×10^{-19} J.

What is the maximum wavelength of incident light that can be shone on this aluminium surface in order to eject electrons?

(A) 9.86×10^{-16} m

(B) 2.96×10^{-7} m

(C) 3.38×10^{6} m

(D) 1.02×10^{15} m

2004 HSC Q14

9. In the photoelectric effect, what happens to the number of electrons when the frequency of light above the threshold energy is kept constant, and the intensity of light increases?

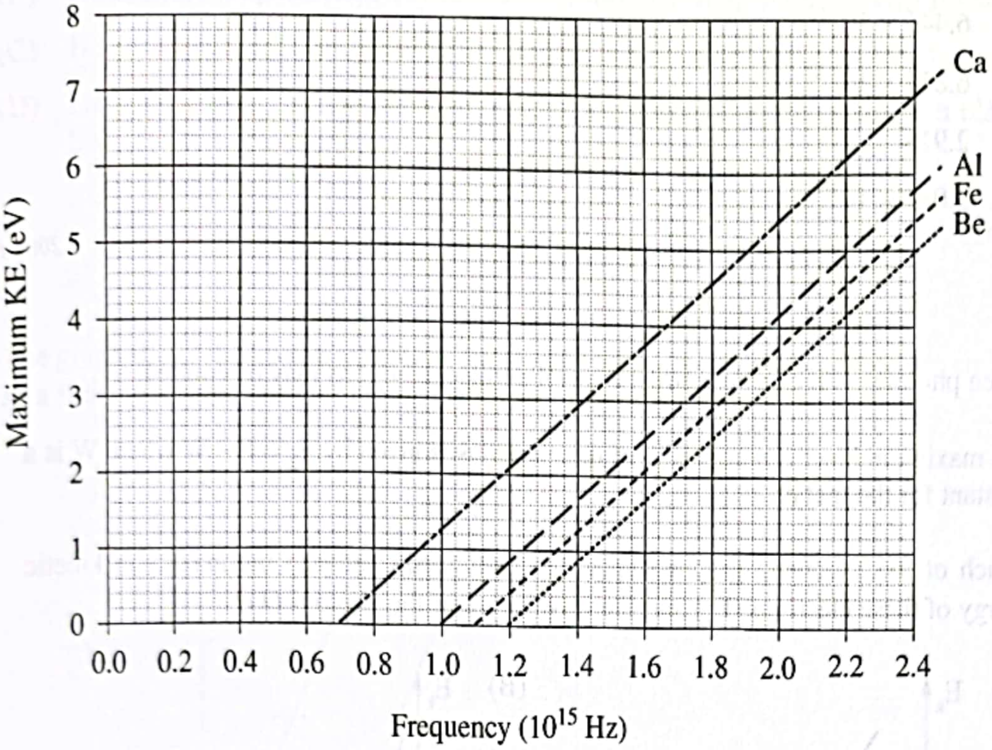
(A) An increase.

(B) A decrease.

(C) The number stays the same.

(D) An initial increase occurs, then a decrease.

10. When electromagnetic radiation shines on metals, photoelectrons may be emitted. The maximum kinetic energy of emitted photoelectrons is plotted against radiation frequency for four metals as shown in the graph.



Electromagnetic radiation of wavelength 187 nm shines upon an unknown metal and the maximum kinetic energy of the photoelectrons is found to be 2.5 eV.

Based on this information, what is the unknown metal?

(A) Al

(B) Be

(C) Ca

(D) Fe

2006 HSC Q15

11. When light of a specific frequency strikes a metal surface, photoelectrons are emitted.

If the light intensity is increased but the frequency remains the same, which row of the table is correct?

	Number of photoelectrons emitted	*Maximum kinetic energy of the photoelectrons*
(A)	Remains the same	Remains the same
(B)	Remains the same	Increases
(C)	Increases	Remains the same
(D)	Increases	Increases

2016 HSC Q13

12. An FM radio station transmits at a frequency of 102.8 MHz.

What is the energy, in joules, of each photon emitted by the transmitter?

(A) 6.446×10^{-42}

(B) 6.812×10^{-26}

(C) 2.918

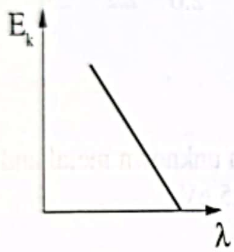
(D) 3.084×10^{16}

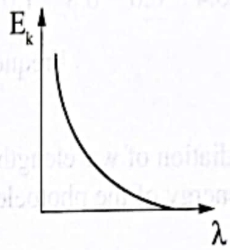
2005 HSC Q14

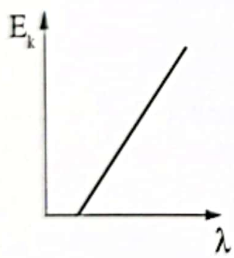
13. When photons with energy E strike a metal surface, electrons may be emitted.

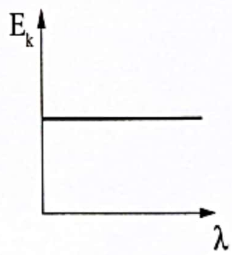
The maximum kinetic energy (E_k) of the electrons is given by $E_k = E - W$ where W is a constant for the metal.

Which of the following graphs shows the relationship between the maximum kinetic energy of these electrons (E_k) and the wavelength of the photons (λ)?

(A)


(B)


(C)


(D)


2011 HSC Q17

14. Blue light is found to cause photoelectric emission from a sodium surface but not from a platinum surface.

Which of the following best accounts for this difference?

(A) Platinum does not absorb photons.

(B) Platinum has more electrons than sodium.

(C) More energy is needed to remove an electron from a platinum surface.

(D) The intensity of the blue light is not high enough to remove electrons from the platinum surface.

2009 HSC Q14

15. What was Max Planck's contribution to the development of quantum physics?

(A) He combined the quantised wave and particle models of light.

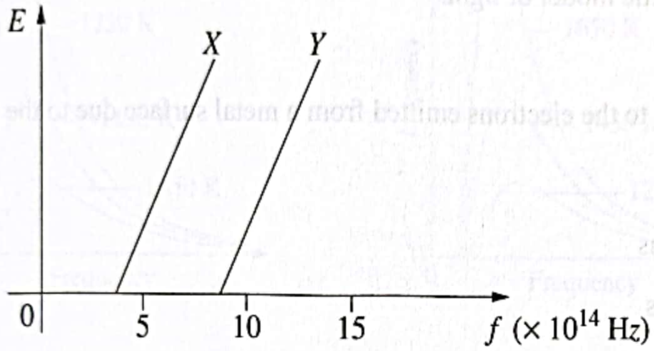
(B) He analysed the photoelectric effect and described light as quantised energy packets.

(C) He explained black body radiation and the photoelectric effect using quantised energy.

(D) He hypothesised that the radiation emitted and absorbed by the walls of a black body cavity is quantised.

2010 HSC Q13

16. The graph shows the maximum kinetic energy (E) with which photoelectrons are emitted as a function of frequency (f) for two different metals X and Y.



The metals are illuminated with light of wavelength 450 nm.

What would be the effect of doubling the intensity of this light without changing the wavelength?

(A) For metal X, the number of photoelectrons emitted would not change but the maximum kinetic energy would increase.

(B) For metal X, the number of photoelectrons emitted would increase but the maximum kinetic energy would remain unchanged.

(C) For both metals X and Y, the number of photoelectrons emitted would not change but the maximum kinetic energy would increase.

(D) For both metals X and Y, the number of photoelectrons emitted would increase but the maximum kinetic energy would remain unchanged.

2013 HSC Q20

17. The following observations relate to the photoelectric effect:

- Energy of the photoelectrons depends on the frequency, not intensity, of the light.
- No electrons are emitted if the light frequency is less than the threshold frequency.
- An increase in the light intensity increases the number of electrons, but not their K_{max}.
- Electrons are ejected almost instantaneously.

Which model of light could not explain these observations?

(A) Wave model of light

(B) Quantum model of light

(C) Photon model of light

(D) Electromagnetic model of light.

18. What name is given to the electrons emitted from a metal surface due to the photoelectric effect?

(A) Photoelectrons

(B) Electron-volts

(C) Quantum electrons

(D) Bohr electrons

19. Sirius is the brightest star in the entire night sky. It is located in the constellation of Canis Major and has a surface temperature of 9940 K.
What is the wavelength of peak intensity for this star?

(A) 27.5 m

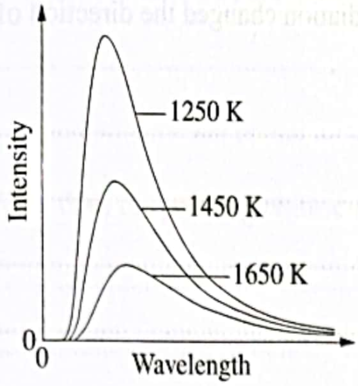
(B) 292 nm

(C) 584 nm

(D) 291.5 m

20. Which graph is consistent with predictions resulting from Planck's hypothesis regarding radiation from hot objects?

A.



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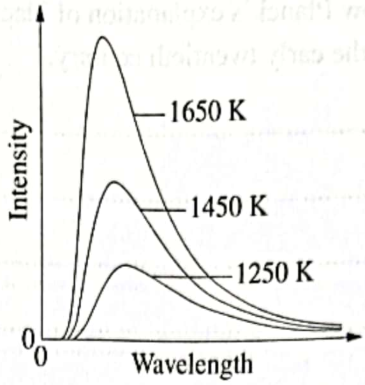

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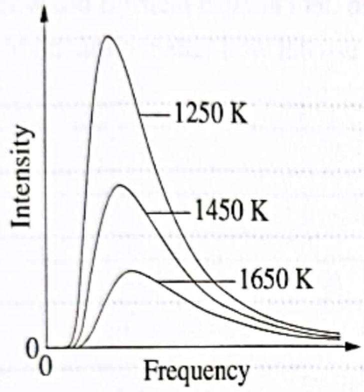

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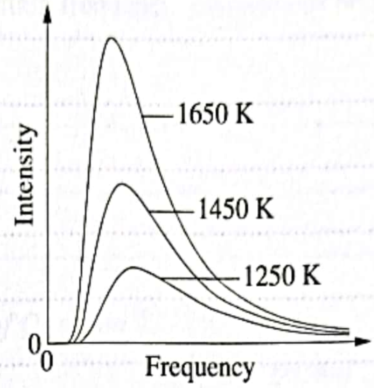
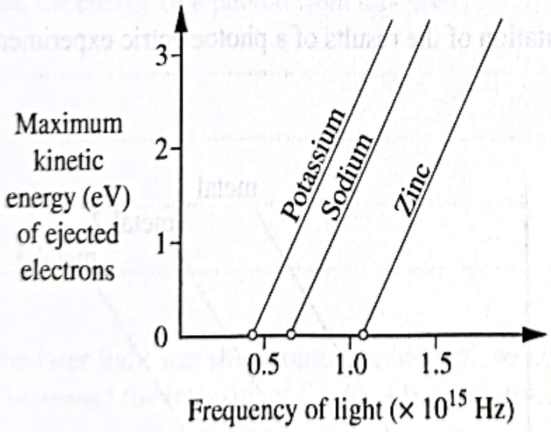


2018 HSC Q2

21. The graph shows the maximum kinetic energy of electrons ejected from different metals as a function of the frequency of the incident light.



What can be deduced from this graph?

A. The maximum kinetic energy of ejected electrons is proportional to the number of photons incident on the metal surface.

B. More photons are required to cause an electron to be ejected from zinc than from potassium.

C. Any photon that can eject an electron from the surface of zinc must also be able to cause an electron to be ejected from potassium.

D. For any given frequency that causes electrons to be ejected from all three metals, the number of electrons ejected is always greatest for potassium.

2018 HSC Q17

Short-answer questions

22. Describe how Planck's explanation of black body radiation changed the direction of scientific thinking in the early twentieth century.

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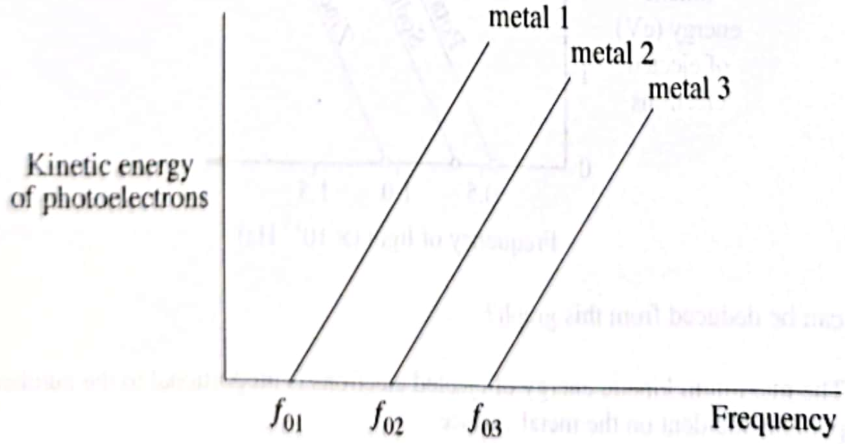
2005 HSC Q23 ... 3 marks

23. Below is a graphical representation of the results of a photoelectric experiment for three different metals.



Question 23 continues

Question 23 (continued)

(a) Why are the slopes of the lines identical?

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(b) What does the point f_{01} represent?

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(c) How did Einstein explain that, below a certain frequency, emission of photoelectrons did not occur no matter how intense the light?

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End of Question 23

1995 HSC Q32B(e) ... 1 + 1 + 1 = 3 marks

24. A physics student was conducting an investigation on the photoelectric effect. The student used an infrared laser with a wavelength of 1.55×10^{-6} m for this investigation.

(a) Calculate the energy of a photon from this laser.

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(b) When the laser light was shone onto a photo-cell, no current was detected. The student increased the intensity of the light but still detected no current.

Explain this observation.

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2003 HSC Q25 ... 2 + 3 = 5 marks

25. Beginning in the late 19th century, observations and experiments on black body radiation and the photoelectric effect led physicists to revise their existing model of light.

Use the above as an example to explain how scientists test and validate models.

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2006 HSC Q26 ... 4 marks

26. Scientists tried to explain observations of black-body radiation using classical wave theory and then quantum theory. How does quantum theory satisfactorily explain black-body radiation?

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2007 HSC Q27(a) ... 3 marks

27. Choose one feature of the photoelectric effect that is not consistent with the wave theory of light. Explain why it is not consistent.

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1982 HSC Q Elective 1L(b) ... 2 marks

28. In a photoelectric experiment, photons are incident on the surface of a metal.

Outline how the release of electrons from the surface depends on each of the following.

(a) Frequency of the light: ....

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(b) Intensity of the light: ....

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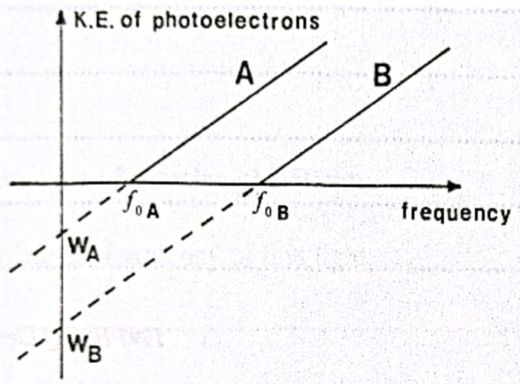
Adapted 1987 HSC Q Elective 1L(b) ... 2 + 1 = 3 marks

29. The graph below shows the kinetic energy of emitted photoelectrons for two metals, **A** and **B** plotted against the frequency of incident radiation.



[Note: W_A and W_B are now designated as Φ for metals **A** and **B**.]

(a) What physical quantity is represented by f_0 for each of the metals **A** and **B**?

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(b) What is the physical significance of the quantities W_A and W_B?

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(c) Why is the concept of a 'quantum' of electromagnetic radiation necessary to explain these graphs?

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1988 HSC Q Elective 1L(c) ... 1 + 1 + 2 = 4 marks

30. Explain how the result of ONE investigation of the photoelectric effect changed the scientific understanding of the nature of light.

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2016 HSC Q27(b) ... 4 marks

31. Light has a dual nature. Describe one situation in which the behavior of light is more easily explained by a particle model than by a wave model.

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1991 HSC Q Elective 1L(c) ... 2 marks

32. (a) What is the energy of a photon having a wavelength of 1000 nm?

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(b) Explain why light having a wavelength longer than a certain value does not produce an electric current in a photocell.

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2010 HSC Q31 ... 2 + 3 = 5 marks

33. Under certain conditions when light is incident on the surface of a metal, electrons are emitted. It is observed that:

- the number of electrons emitted is proportional to the intensity of light
- the kinetic energy of the electrons emitted is proportional to the frequency of the radiation.

Explain each of these observations in terms of Einstein's quantum model of light.

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1993 HSC Q Elective 1L(e) ... 2 + 2 = 4 marks

34. A laser emits light of wavelength 550 nm.

(a) Calculate the frequency of this light.

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(b) The electrons in a specific metal must absorb a minimum of 5×10^{-19} J in order to be ejected from its surface.

Explain why electrons will not be ejected from this metal when photons of wavelength 550 nm strike its surface. Support your answer with relevant calculations.

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2017 HSC Q21 ... 2 + 3 = 5 marks

35. What experimental evidence was Planck attempting to explain with the introduction of the quantum of light?

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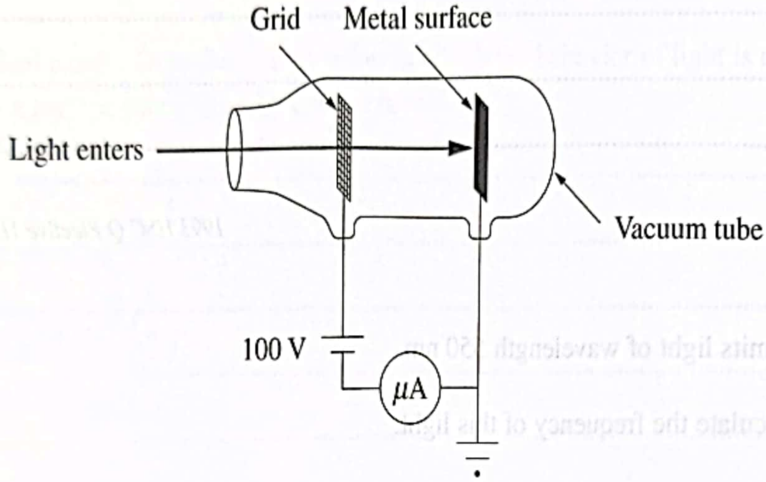
1993 HSC Q Elective 1L(d) ... 2 marks

36. A student conducts an experiment using a photoelectric cell as shown in the diagram.



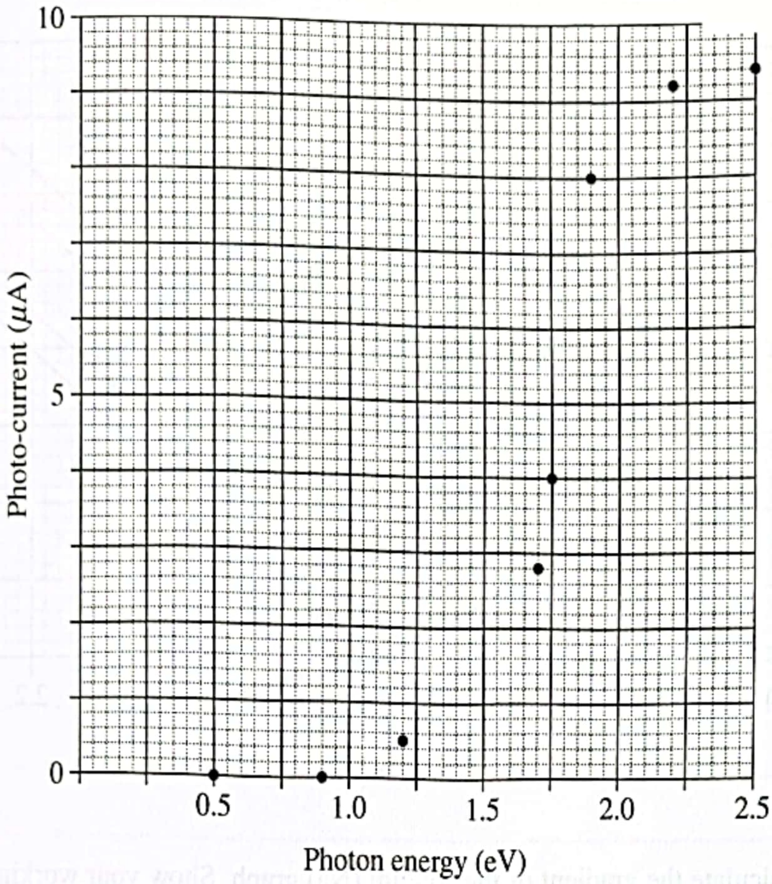
Light is shone through a grid onto a metal surface. The metal is at earth potential and the grid is at 100 V, so that any electrons emitted from the surface produce a current in the external circuit.

The student shines light sources of different photon energies onto the metal surface and records the current flowing for each. The light sources are adjusted so that their intensities are equal. The results are recorded in the table and shown on the graph.

Photon energy (eV)	*Photo-current* (μA)
0.50	0
0.90	0
1.20	0.5
1.70	2.8
1.75	4.0
1.90	8.0
2.20	9.2
2.50	9.4

Question 36 continues

Question 36 (continued)



(a) On the grid provided, draw the straight line of best fit in the region where the photo-current varies greatest with photon energy.

(b) From the line drawn on your graph, estimate the minimum energy (work function) for photoelectric emission.

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(c) The experiment is repeated, but the intensities of the light sources are doubled. Predict the results of this new experiment by drawing a second line on the graph.

(d) Justify the line you have drawn in part (c).

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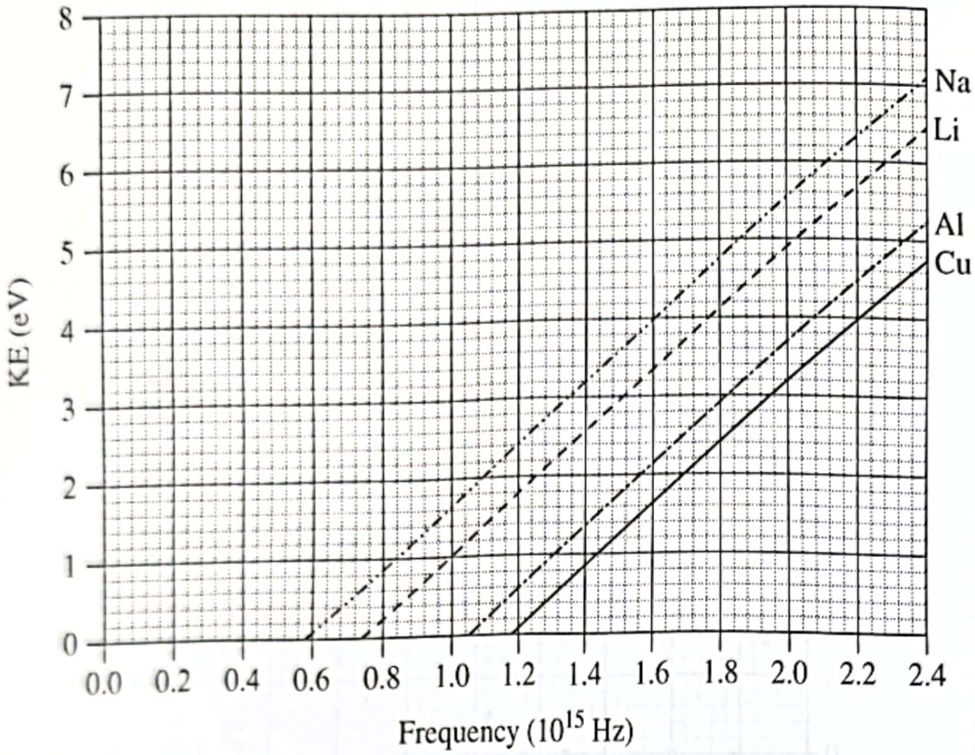
End of Question 36

2005 HSC Q25 ... 1 + 1+ 2 + 2 = 6 marks

37. An experiment was conducted in which light of different frequencies was shone onto the surfaces of four different metals. Electrons were found to be emitted and their kinetic energies were measured. The graph shows the results.



(a) Calculate the gradient of the sodium (Na) graph. Show your working.

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(b) Each of the graphs has the same gradient. What is the significance of this observation?

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2007 HSC Q27(c) ... 2 + 1 = 3 marks

38. (a) Calculate the number of photons, $\lambda = 450$ nm, which are required to transfer 1.0×10^{-3} J of energy.

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(b) A 1 W beam of light transfers 1 J per second from one point to another.

With reference to the particle model of light, contrast a 1 W beam of red light and a 1 W beam of blue light.

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2011 HSC Q29 ... 3 + 2 = 5 marks

39. The concept of light as a stream of photons was developed from the work of Einstein.

(a) State one way in which photons differ from Newton's 'light corpuscles'.

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(b) Calculate the energy of a photon of yellow light of wavelength 550 nm.

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1991 HSC Q Elective 1L(d) ... 1 + 2 = 3 marks

40. (a) In considering the photoelectric effect, explain what is meant by the work function of a metal.

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(b) Suppose that light at the red end of the visible spectrum has a wavelength of 700 nm, whilst that at the violet end has a wavelength of 400 nm. Sodium metal has a work function of 2.28 eV.

Show which, if any, of the above two wavelengths will produce the photoelectric effect in sodium.

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1998 HSC Q32B(c) ... 2 + 3 = 5 marks

41. Monochromatic light of wavelength 650 nm is incident on a clean sodium surface of work function 3.7×10^{-19} J.

(a) Determine the energy of a photon of this light.

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(b) Would the photoelectric effect be evident in this sample? Explain your answer.

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(c) The intensity of this light is now increased. How does this affect the emission of electrons from the sodium surface? Explain your answer.

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1999 HSC Q32B(d) ... 1 + 2 + 2 = 5 marks

42. Astronomers investigating Antares, a red giant star in the constellation Scorpius, measured the intensity of radiation coming from it. They determined that its peak radiation intensity occurs at a wavelength of 850 nm.

What is the surface temperature of this star?

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2 marks

43. (a) Calculate the energy of a photon of wavelength 415 nm.

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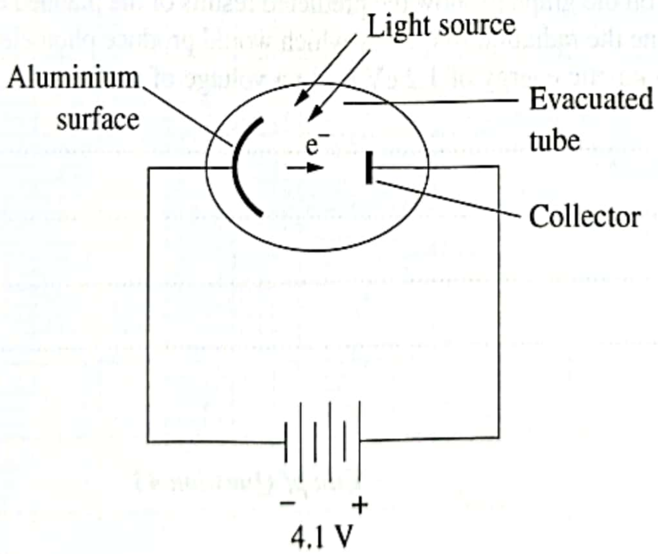
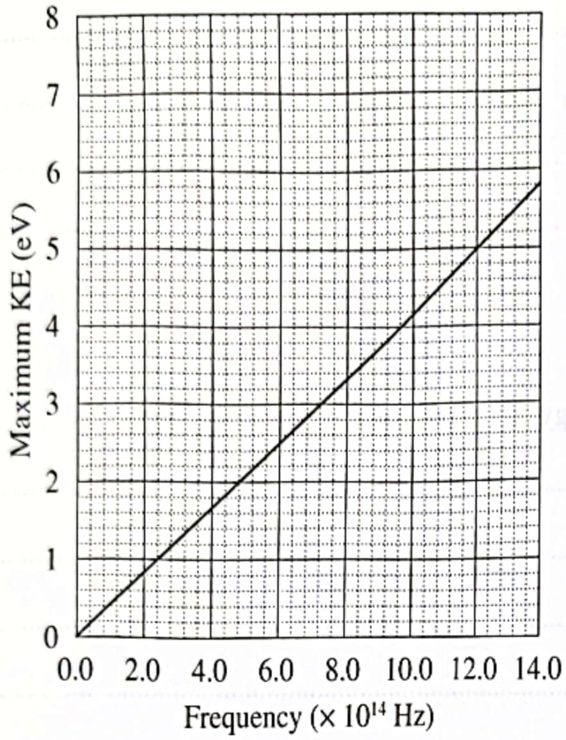
(b) An experiment was conducted using a photoelectric cell as shown in the diagram.



Question 43 continues

Question 43 (continued)

The graph plots the maximum kinetic energy of the emitted photoelectrons against radiation frequency for the aluminium surface.



The experiment is planned to be repeated using a voltage of 0.0 V.

Draw a line on the graph to show the predicted results of the planned experiment, and determine the radiation frequency which would produce photoelectrons with a maximum kinetic energy of 1.2 eV using a voltage of 0.0 V.

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End pf Question 43

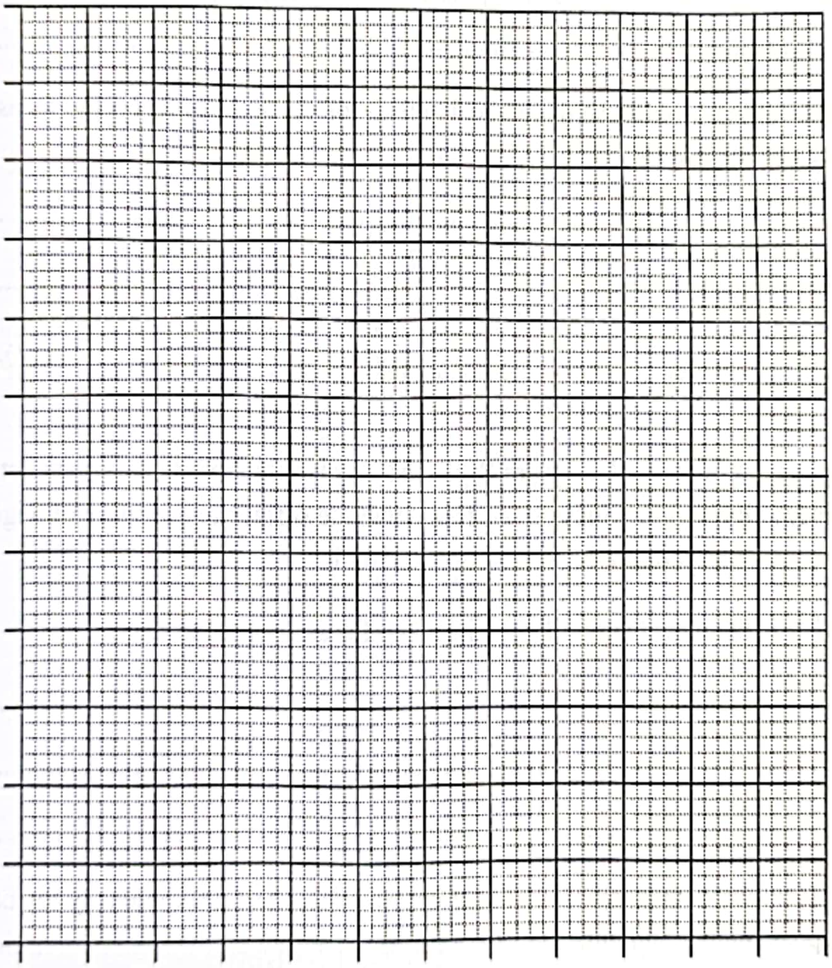
2014 HSC Q26 ... 2 + 3 = 5 marks

44. A student carried out an experiment on the photoelectric effect. The frequency of the incident radiation and the energy of the photoelectrons were both determined from measurements taken during the experiment.

The results obtained are shown in the table:

Frequency of incident radiation ($\times 10^{14}$ Hz)	*Energy of photoelectrons* ($\times 10^{-19}$ J)
6.9	1.22
8.2	1.70
9.1	3.70
9.9	3.05
10.6	3.38
11.8	3.91

(a) Graph these results on the grid, including the line of best fit.



(b) How could the reliability of the experiment be improved?

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2001 HSC Q25 ... 4 + 2 marks = 6 marks

45. In an experiment to investigate the photoelectric effect, light is shone onto a silver surface and the resulting maximum electron kinetic energy is measured and recorded.

Light wavelength (nm)	*Electron kinetic energy* (eV)
250	0.25
215	1.08
187	1.90
167	2.73
150	3.56

(a) Determine the frequency of the highest energy photons used in the experiment.

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(b) What effect would changing the intensity of the light have on the measured electron kinetic energy?

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2009 HSC Q27(a), (b) ... 2 + 1 = 3 marks

46. Two bright stars in the night sky are Rigel and Betelgeuse, both in the constellation Orion. Astronomers investigating these stars, found that the surface temperature of Rigel is 11,000 K and the surface temperature of Betelgeuse is 3500 K.

(a) What is the wavelength of peak intensity for each of these stars?

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(b) Astronomers have determined that the wavelength of peak intensity for Earth's Sun is approximately 500 nm.

Calculate the Sun's surface temperature and then rank Rigel, Betelgeuse and the Sun in order from highest to lowest surface temperature.

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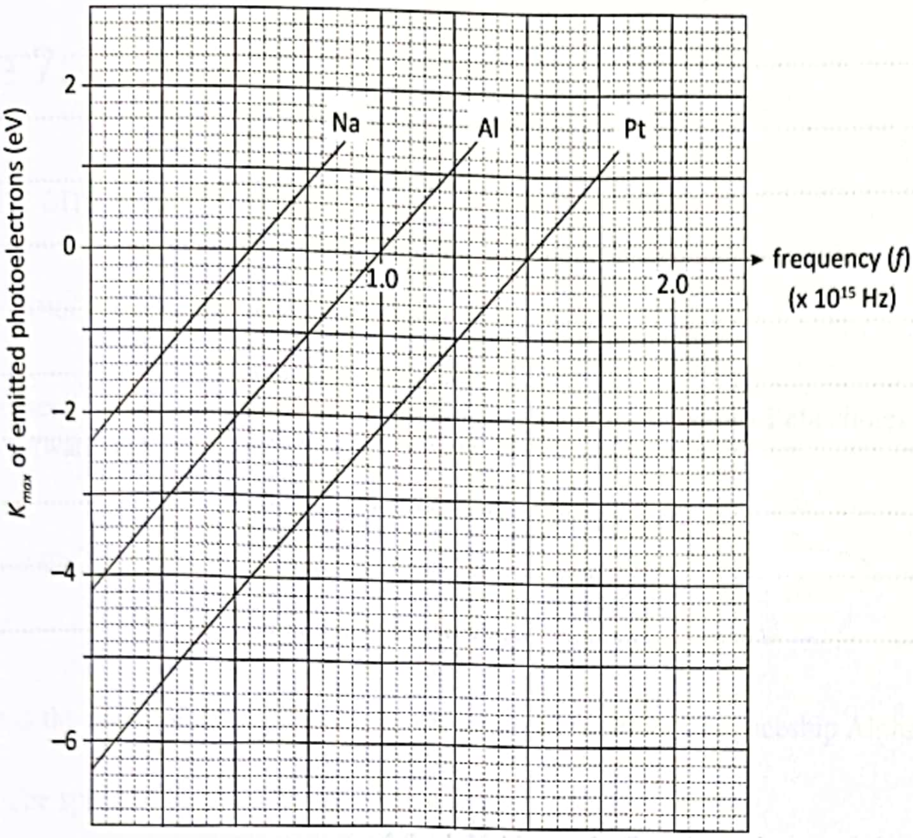
... 3 + 2 = 5 marks

47. The graph below shows the maximum kinetic energy of the emitted photoelectrons versus the frequency of light for three different metals.



(a) From the graph above, determine the threshold frequency and work function for each of the metals. In the space below, construct a table to give your answers.

(b) If ultraviolet light with a frequency of 2.2×10^{15} Hz shines on the aluminium, what effect will this have on the emission of photoelectrons from the surface of the aluminium? Explain your answer.

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... 3 + 2 = 5 marks

48. Explain how the law of conservation of energy and the photon model of light apply to the photoelectric effect $K_{max} = hf - \phi$ as it occurs in metallic elements.

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... 4 marks

49. The Earth is sometimes described as a 'black body'.

Explain whether this description is valid or not.

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3 marks

7.3 Light: Quantum Model

Multiple choice: 1 mark each

1. B	**2.** A	**3.** A	**4.** B	**5.** C	**6.** D	**7.** A	**8.** B
9. A	**10.** A	**11.** C	**12.** B	**13.** B	**14.** C	**15.** D	**16.** B
17. A	**18.** A	**19.** B	**20.** B				

Explanations:

1. B Max Planck derived an empirical formula for black body radiation that exactly fitted with experimental observation. It involved what was then a radical hypothesis – that light is quantised with the energy carried by light being proportional to the frequency of the light, as in (B).

2. A The black body radiation curves for different temperatures were unable to be explained by classical physics. Max Planck derived empirical equations that accurately fitted and predicted black body radiation curves. For it to work, the assumption had to be made that energy jumps were quantised and not continuous, so (A) is the answer. Einstein, Rutherford and Bohr incorporated Planck's work into their own later ideas, so (B), (C) and (D) are incorrect.

3. A Max Planck believed that hot objects did not emit energy continuously in waves (as in classical physics). He proposed that energy was emitted as small discrete packets of energy, now called quanta. Albert Einstein adopted the idea that electromagnetic radiation has a dual wave-particle nature and combined it with Planck's hypothesis that the energy of radiation was quantised. Hence Einstein hypothesised that light itself is quantised, i.e. each photon carries a discrete package of energy. So (A) is the answer.

4. B A black body radiation curve shows that after a maximum intensity of black body radiation is reached, the intensity decreases rapidly at shorter wavelengths. The shorter the wavelength, the greater the energy of each photon. At short wavelengths, a photon requires energy that is high compared to the average thermal energy, and so there are less photons at short wavelengths. So (B) is the answer. Short wavelength photons have higher not lower energy, so (A) is incorrect. A black body absorbs all incident radiation, so (C) is incorrect. Destructive interference occurs at both short and long wavelengths in a black body cavity, so (D) is incorrect.

5. C The lines for all of the metals are parallel and so they have the same gradient (slope) equal to Planck's constant, as the energy-frequency relation is constant for all materials. So (C) is the answer. Each metal *A*, *B* and *C* has a different work function, a different threshold frequency and the photoelectron that are released would have a different amount of kinetic energy. So (A), (B) and (D) are all incorrect.

6. **D** A photoelectron will be ejected only if the frequency of the incident light is greater than the threshold frequency. So (D) is the incorrect statement and therefore the answer.

7. **A** The equation, $E_{k(\max)} = hf - \phi$ is that of a straight line, which is the result of plotting values of $E_{k(\max)}$ onto the vertical (Y) axis of a graph with frequency on the horizontal (X) axis. This is similar to $y = mx + b$. The gradient (slope) of the line is Planck's constant, h, so (A) is the correct answer. The constant, f, is the intercept on the Y axis.

8. **B** The energy of a photon decreases as its wavelength increases. Therefore, the maximum wavelength of incident light that will eject electrons has just sufficient energy to eject an electron.

For a photon, $E = hf = \frac{hc}{\lambda} = \frac{6.626 \times 10^{-34} \times 3.00 \times 10^{8}}{\lambda} = 6.72 \times 10^{-19}$ joules

$\therefore\ \lambda = \frac{6.626 \times 10^{-34} \times 3.00 \times 10^{8}}{6.72 \times 10^{-19}} = 2.958 \times 10^{-7} = 2.96 \times 10^{-7}$ m, so (B) is the answer.

9. **A** In the photoelectric effect, an increased intensity of light results in a greater rate of electrons being released … as in (A).

10. **A** $c = f\lambda$ Hence the frequency of unknown metal: $f = \frac{c}{\lambda} = \frac{3 \times 10^{8}}{187 \times 10^{-9}} = 1.60 \times 10^{15}$ Hz

When frequency = 1.60×10^{15} Hz and the maximum $KE = 2.5$ eV, the point of intersection is on the line for aluminium (Al). So (A) is the answer.

[Note: Remember to convert the 187 nm to metres before using in the equation.]

11. **C** As the intensity of light is increased, more photons will be emitted. As these photons hit the metal surface, more photoelectrons will be ejected, as in (C) and (D). The energy of the photoelectrons depends on their frequency. Since the frequency remains the same, the maximum kinetic energy will also remain the same, as in (A) and (C) (since $E = hf$). So (C) is the answer.

12. **B** $E = hf$

$= 6.626 \times 10^{-34} \times 102.8 \times 10^{6}$

$= 6.812 \times 10^{26}$ J … as in (B).

13. **B** $E_k = E - W$ and $E = hf = h\frac{c}{\lambda}$ (since $c = f\lambda$). So $E_k = h\frac{c}{\lambda} - W$. Hence $E_k \propto \frac{1}{\lambda}$

So the shorter the wavelength of the incident photons, the greater will be the E_k of the emitted electrons. Photons greater in wavelength than that corresponding to the work function will not emit electrons and E_k will become zero at that value of λ. The graph for such a relationship is an hyperbola, as in (B). It is not a linear relationship as in (A) and (C). (D) is incorrect as it shows E_k as a constant independent of λ.

[Note: In this graph, E_k is plotted against wavelength rather than the more usual graphs that plot E_k against frequency or against the reciprocal of wavelength, which both give straight lines ... similar to the one in (C).]

14. **C** All metals absorb photons, so (A) is incorrect. Platinum does have more electrons than sodium, but this is irrelevant to the photoelectric effect in platinum, so (B) is incorrect. If blue light does not have sufficient energy to eject electrons, light of greater energy such as violet or even ultraviolet light might be required, so (C) is the answer. It is the energy of the incident light and not its intensity that produces the photoelectric effect, so (D) is incorrect.

15. **D** Planck hypothesised that radiation was quantised, so (D) is the answer. Neils Bohr, and not Planck, combined the particle and wave nature of light with his principle of complementarity, so (A) is incorrect. Einstein, and not Planck, analysed and explained black body radiation and the photoelectric effect. So both (B) and (C) are incorrect.

16. **B** Photons of light with a 450 nm wavelength have a frequency of 6.67×10^{14} Hz (since $f = \frac{c}{\lambda}$), so have sufficient energy to emit photoelectrons from metal *X*. However, the graph shows that this frequency is insufficient to eject photoelectrons from metal *Y*. By increasing the light intensity, there will be more photons striking both metals. So more photoelectrons will be ejected from metal *X*. Since each of the photons still has the same energy, no photoelectrons will be ejected from metal *Y* and the kinetic energy of the ejected photoelectrons will remain the same. So (B) is the only possible answer.

17. **A** The four observations listed are contrary to the predictions of the wave model of light So (A) is the answer. They are consistent with the quantum model of light that includes the concept of photons so both (B) and (C) are incorrect. Light is a form of electromagnetic radiation in both the quantum and the wave model of light so (D) is incorrect.

18. **A** The electrons emitted from a metal surface due to the photoelectric effect are called photoelectrons. So (A) is the answer.

19. **B** $\lambda_{max} = \frac{b}{T} = \frac{2.898 \times 10^{-3}}{9940} = 291.5 \times 10^{-9}\ \text{m} \approx 292\ \text{nm}$

So (B) is the answer.

20. **B** The peak radiation frequency is higher (and the corresponding wavelength is shorter), as the temperature increases. This is correctly shown for wavelength in (B), while (A) incorrectly shows the opposite. So (B) is the answer. Both (C) and (D) show the reverse of the correct relationships for frequency.

21. **C** The graphs show the relationship between K_{max} of electrons and the frequency of the incident light. It does not show the number of photons (intensity of light). So, neither (A) nor (B) can be deduced from the graph. The graph does show that higher energy photons (i.e. higher frequency) are required to eject electrons from zinc, than from sodium or potassium. This means that this energy will also eject electrons from sodium and potassium.So (C) is a correct deduction from the graph. The does not provide information about the number of photoelectrons. So (D) is not a valid conclusion.

22. Around 1900, scientists thought the energy absorbed and emitted by a black body should be continuous, and as the body became hotter, the intensity should increase at shorter wavelengths. This idea was not supported by experimental data, which showed that the amount of energy radiated reached a maximum at a wavelength that depended on the temperature of the black body, and at lower wavelengths (higher frequencies) that the peak the intensity decreased and then dropped to zero for the shorter UV wavelengths. Hence Planck suggested that radiation was emitted or absorbed by a black body in discrete amounts (i.e. packets of energy that were later called quanta) rather than continuously. This explained the results that had been observed in experiments and led to the 'quantum theory' that became the basis of modern physics.

23. (a) The slope of each line is Planck's constant, h, since $E = hf$.

(b) f_{01} represents the threshold frequency for metal 1.

(c) Photons of light with frequency below f_0 lack sufficient energy (work function) to displace an electron.

[Note: A photon transfers either all or none of its energy to the electron.]

24. (a) For a photon, $E = hf$ and $c = f\lambda$

$$\therefore\ E = \frac{hc}{\lambda} = \frac{6.626 \times 10^{-34} \times 3.00 \times 10^{8}}{1.55 \times 10^{-6}}$$

$$= 1.28245 \times 10^{-19}$$

$$= 1.28 \times 10^{-19} \text{ Joules}$$

(b) Current will only be detected if the photoelectric effect occurs. Electrons will only be released if the energy of the light photons is equal to, or greater than, the energy required by the electrons to overcome the forces binding them to the surface. The energy of a photon depends on the frequency of the light, not the light intensity. In this case, the frequency and hence the energy of the light must be too low to release electrons from the photocell.

[Note: Increasing the light intensity increases the number of photons but does not increase the energy of the photons. If individual photons have insufficient energy, no photoelectrons are released from the photocell.]

25.

Steps in testing and validating models	*How scientists were led to revise their existing model of light*
• Scientists propose a theory / hypothesis.	In late 19th century, scientists hypothesised that light was a continuous wave.
• Scientists then perform investigations and experiments to test the hypothesis.	Observations and experiments on black body radiation and photoelectric effect were done.
• Scientists examine the results and determine if they support/refute the hypothesis.	Black body results were unexpected, e.g. 'UV catastrophe' – so the photoelectric effect had no time delay for photoemission in very dim light. Scientists realised that existing theories did not explain these results.
• If needed, scientists revise their thinking and propose a new hypothesis / theory and then re-test this.	Planck suggested a mathematical theory that light came in small packets of energy called 'quanta', instead of being continuous.

26. Planck proposed that the radiation emitted or absorbed by a black body was exchanged in discrete amounts (packets of energy), later called quanta, rather than continuously as in classical physics. The size of each quantum of energy was characteristic of the frequency of light emitted. Planck's black-body radiation curves showed that most of the energy is emitted at a peak wavelength dependent on the temperature and that each quanta of energy (E) could be described by hf. This explained the nature of the radiation emitted in experiments.

27. The photoelectric effect showed that the energy of ejected electrons was proportional to the frequency and not the intensity of light, and that no electrons were ejected below a threshold frequency. These observations could not be explained by classical wave theory, as this predicted that light of any wavelength would eject electrons.

28. (a) There is a minimum threshold frequency required to cause the emission of photoelectrons, regardless of the intensity of the light. The number of electrons released is independent of the frequency of the light.

(b) Increasing the intensity of the light, increases the number of photoelectrons emitted – not their energy.

29. (a) f_0 is the threshold frequency for a particular metal (below which the photoelectric effect does not occur).

(b) W_A and W_B are the minimum energy required to remove a photoelectron from the surface of metals **A** and **B** respectively (i.e. they are the work function (Φ) of metals **A** and **B**).

[Note: The symbol now used in the Physics Syllabus for the work function is Φ instead of W.]

(c) The quantum concept, that electromagnetic radiation is transmitted as discrete quanta of energy called photons, explains why no electrons are ejected below a threshold frequency (f_0) and that the kinetic energy of ejected electrons is proportional to the frequency.

30. One investigation showed that the maximum kinetic energy of the photoelectrons was related to the frequency of the light, but not to the light intensity. The wave model did not predict this result. However, explaining light as consisting of discrete 'packets' or 'quanta' of energy that have energy proportional to their frequency did. This changed the understanding of light, as it showed that light could behave as a particle and not just as a wave.

31. The photoelectric effect shows that the energy of electrons ejected from a metal surface are proportional to the frequency and not to the intensity of light, and that no electrons are ejected below a threshold frequency. These observations can only be explained by a particle model, and not by a wave model.

32. (a) $E = hf$ and $c = f\lambda$ so $E = h\frac{c}{\lambda} = 6.626 \times 10^{-34} \times \frac{3.00 \times 10^{8}}{1000 \times 10^{-9}}$ J

$\therefore E = 1.9878 \times 10^{-19} = 1.99 \times 10^{-19}$ J

(b) Photocells rely on the photoelectric effect for their operation. In any photocell, electrons are held within the metal surface by attractive forces, so a minimum energy ($E = \frac{c}{\lambda}$) that is characteristic of the metal is required for an electron to be removed from its surface. The ejected electrons form the photocell current. The minimum energy required is called the work function (ϕ) for each element. For each metal, there will be a maximum λ corresponding to its ϕ. Light of longer wavelengths has insufficient energy to allow photoelectrons to be emitted.

33.
- If the intensity of light increases, there are more photons to eject electrons. So, if electrons are emitted, the number of electrons increases as the intensity of light increases.
- When a photon strikes a metal, it can interact with a single electron, transferring all of its energy (hf) to the electron. Any remaining energy after an electron has been emitted from the metal will appear as its kinetic energy. Hence a photon's frequency is related to the kinetic energy of the electrons emitted.

34. (a) $c = f\lambda \;\therefore f = \frac{c}{\lambda} = \frac{3.00 \times 10^{8}}{550 \times 10^{-9}} = 5.45 \times 10^{14}$ Hz

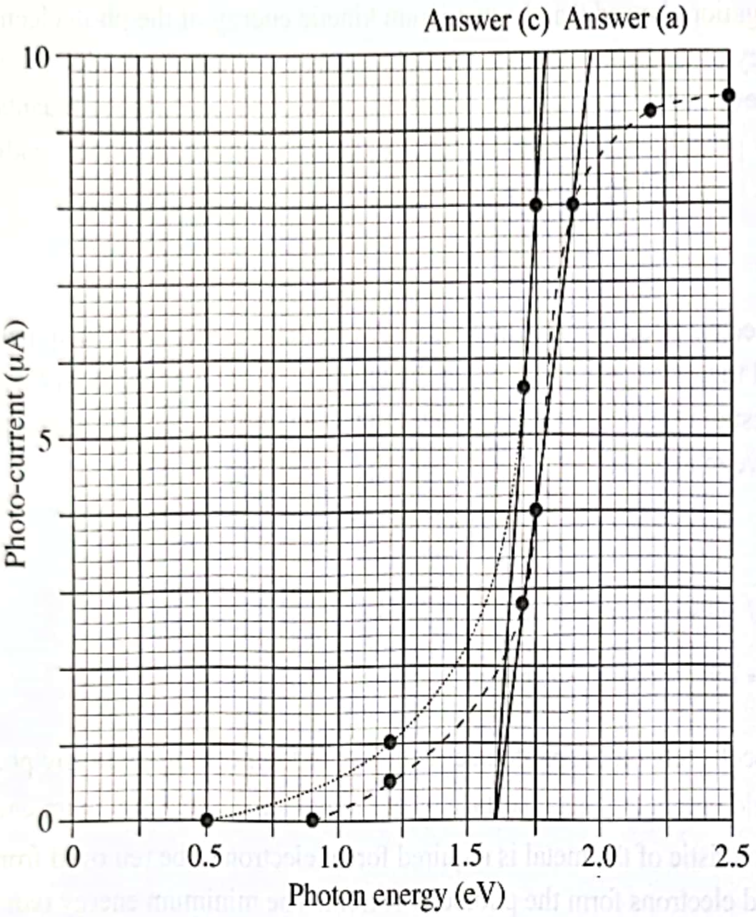
(b) Minimum energy of incoming photons must be $>5 \times 10^{-19}$ J for electrons to be ejected from this metal's surface. Energy of each photon of wavelength 550 nm is:

$$E_{photon} = hf = 6.626 \times 10^{-34} \times 5.45 \times 10^{14} = 3.61 \times 10^{-19}\text{ J}$$

$\therefore$ since this is $< 5 \times 10^{-19}$ J, photons of 550 nm wavelength lack sufficient energy to eject electrons from this metal.

35. Planck was trying to explain black body radiation curves for different temperatures that could not be explained by classical physics. These experimental curves had an unexpected lack of higher frequencies in the frequency distribution that classical physics had predicted.

36. (a) & (c)



(b) 1.6 eV

(c) *See graph above.*

(d) If the light intensity is doubled, there will be twice as many photons in the light beam. For photons with energy equal to or greater than the work function, there will be double the number of electrons being released from the metal surface, and so the photo-current will double, as shown by line (c) on the graph.

37. (a) Gradient (slope) $= \frac{\text{rise}}{\text{run}} = \frac{7.1 - 0.1}{(2.4 - 0.6) \times 10^{15}} = \frac{7.0}{1.8 \times 10^{15}} = 3.9 \times 10^{-15}\text{eV s}$

[Note: When frequency is plotted against KE (= K), the slope is h, Planck's constant, as $E = hf$. The value here is different to that on the Data Sheet for Planck's constant, as the units being used here are not SI units.]

(b) It shows that the kinetic energy (K) of the electrons emitted from each metal is proportional to the frequency of the light used. The gradient is Planck's constant.

[Note: Each metal has a different threshold frequency as the work function, ϕ, is different for each metal, and since $E = hf = \phi + K$.]

38. (a) $E = hf$ and $c = f\lambda$ $\therefore$ $E = \frac{hc}{\lambda}$

$$E_{photon} = \frac{6.626\times10^{-34}\times3.00\times10^{8}}{450\times10^{-9}} = 4.417\times10^{-19} \text{ J}$$

$$\text{Number of photons} = \frac{E_{total}}{E_{photon}} = \frac{1.0\times10^{-3}}{4.417\times10^{-19}} = 2.26\times10^{15}$$

(b) Red light has a longer wavelength (λ = 700 nm) and lower frequency than blue light (λ = 450 nm). Since $E = hf$, red photons will have less energy than blue photons. Therefore, a 1 W beam of red light will contain more photons than a 1 W beam of blue light and so will be more intense (brighter).

[Note: Red light, $E_{photon} = \frac{6.626\times10^{-34}\times3.00\times10^{8}}{700\times10^{-9}} = 2.840\times10^{-19}$ J

whereas for blue light, $E_{photon} = 4.417\times10^{-19}$ J, as calculated in part (a).]

39. (a) Newton's light corpuscles were small physical particles, whereas photons are the energy in a quantum (or discrete packet) of light.

(b) $E = hf$ and $f = \frac{c}{\lambda}$

$$\therefore E = \frac{hc}{\lambda} = \frac{6.626\times10^{-34}\times3\times10^{8}}{550\times10^{-9}} = 3.6\times10^{-19} \text{ J}$$

40. (a) The work function (ϕ) is the minimum energy necessary to overcome the attractive forces holding electrons in a metal's surface. This relationship is shown in the equation:

$$hf = hf_0 + \tfrac{1}{2}mv^2 = \phi + \tfrac{1}{2}mv^2$$

(b) For red light: $f_0 = \frac{hc}{\lambda} = \frac{6.626\times10^{-34}\times3\times10^{8}}{700\times10^{-9}} = 2.8397\times10^{-19}$ J

$= \frac{2.8397\times10^{-19}}{1.602\times10^{-19}} = 1.773$ eV (since 1 eV = 1.602×10^{-19} J)

This photon energy is less than the work function, so no electrons are ejected.

For violet light: $f_0 = \frac{hc}{\lambda} = \frac{6.626\times10^{-34}\times3\times10^{8}}{400\times10^{-9}} = 4.9695\times10^{-19}$ J

$= \frac{4.9695\times10^{-19}}{1.602\times10^{-19}} = 3.102$ eV

This photon energy is greater than the work function, so electrons will be rejected.

$\therefore$ the photoelectric effect will occur in sodium with violet light, but not with red light.

41. (a) $E = hf = \dfrac{hc}{\lambda}$

$$= \frac{6.626 \times 10^{-34} \times 3 \times 10^{8}}{650 \times 10^{-9}} = 3.1 \times 10^{-19}\ \text{J}$$

(b) No. The energy of the light is less than the work function, so that even if an electron absorbs a photon, it will still have insufficient energy to overcome the attractive forces and escape from the sodium.

(c) It has no effect, since intensity is determined by the number of photons and not by their energy. Each of the additional photons still has the same amount of energy which is less than the work function.

42. Since $\lambda_{max} = \dfrac{b}{T}$

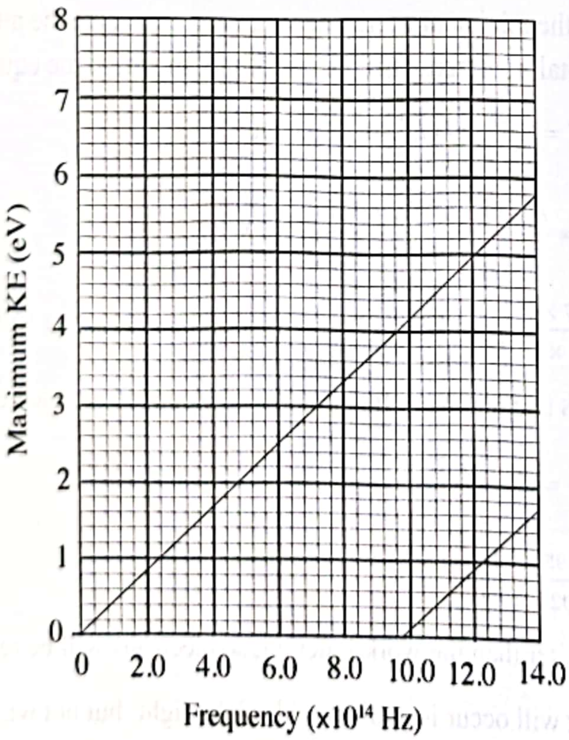
$$T = \frac{b}{\lambda_{max}} = \frac{2.898 \times 10^{-3}}{850 \times 10^{-9}} = 3409.4\ \text{K}$$

$\therefore$ surface temperature of Antares is 3410 K.

43. (a) $c = f\lambda \quad \therefore f = \dfrac{c}{\lambda}$ This can be substituted into $E = hf$

$$\therefore E = \frac{hc}{\lambda} = \frac{6.626 \times 10^{-34} \times 3.00 \times 10^{8}}{415 \times 10^{-9}}\ \text{J} = 4.79 \times 10^{-19}\ \text{J}$$

(b)



[Note: $E = hf = \phi + E_k$. So $E_k = hf - \phi$

So all graphs of maximum E_k (KE) versus frequency have a slope equal to Planck's constant.

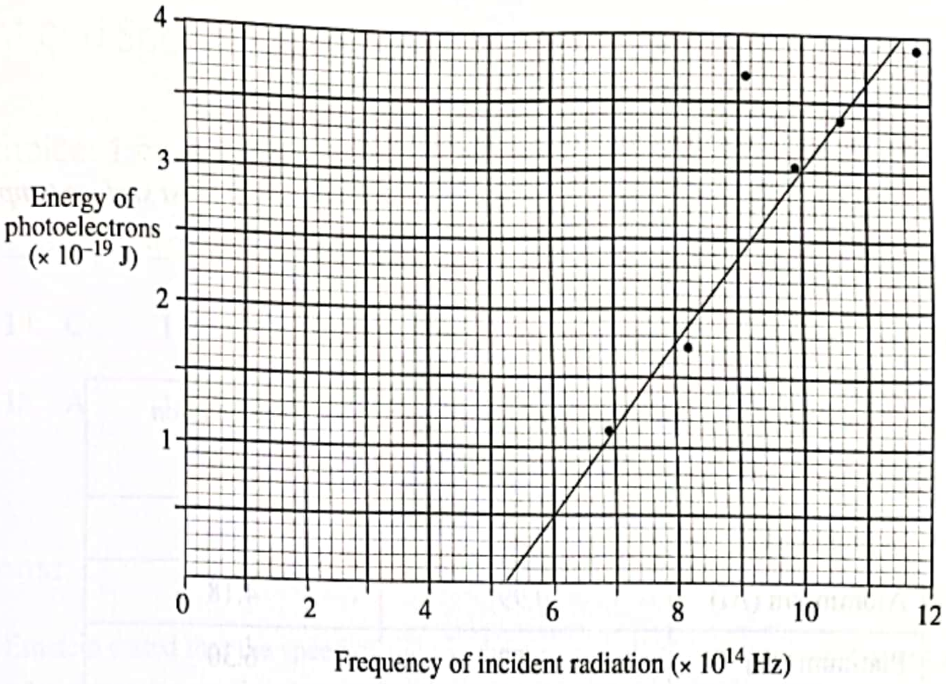
Hence the required line will be *parallel* to the one given in the question.

The applied voltage is reduced from 4.1 V to 0.0 V for the repeat of the experiment. So the Y-axis intercept has to be 4.1 eV lower.]

From the graph: At maximum E_k (KE or K) = 1.2 eV

Radiation frequency = 12.8×10^{14} Hz = 1.28×10^{15} Hz

44. (a)



[Note: Always place the independent variable (frequency) on the horizontal axis. Linear scales should always be used on the axes. You will not necessarily need all the grid provided in a question. In this case, 0–4 fits best for plotting purposes over 8 cm on the Y-axis. When doing a line of best fit, an obviously discrepant result as for frequency 9.1×10^{14} Hz should be ignored.]

(b) *Any TWO of the following:*

- The experiment could be repeated a number of times using the same equipment/resources and under the same conditions, e.g. temperatures, and for the same values of the independent variable; and the mean (average) value of the each trial could be calculated and plotted.
- Measurements could be taken at a greater range of frequencies.
- The measuring equipment should be calibrated after each trial.

45. (a) The shorter the wavelength, the higher the photon energy – so the highest energy photons will be those with wavelength of 150 nm.

$v = f\lambda$ so $c = f\lambda$

$\therefore$ Frequency, $f = \frac{c}{\lambda} = \frac{3.00 \times 10^{8}}{150 \times 10^{-9}} = 2.00 \times 10^{15}$ Hz

(b) It has no effect on the measured electron kinetic energy.

[Note: A change in intensity determines the number of photoelectrons released per unit time, as it increases or decreases the current in proportion to the intensity.]

46. (a) Since $\lambda_{max} = \frac{b}{T}$

Rigel: $\lambda_{max} = \frac{2.898 \times 10^{-3}}{11{,}000} = 2.63 \times 10^{-7}$ m

Betelgeuse: $\lambda_{max} = \frac{2.898 \times 10^{-3}}{3500} = 8.28 \times 10^{-7}$ m

(b) *Earth's Sun*: $T = \frac{b}{\lambda_{max}} = \frac{2.898 \times 10^{-3}}{500 \times 10^{-9}} = 5796$ K

So, the surface temperature of Sun is 5800 K.

$\therefore$ *highest surface temperature* ⟷ *lowest surface temperature*

Rigel Sun Betelgeuse

47. (a)

Metal	*Threshold frequency* ($\times 10^{15}$ *Hz*)	*Work function* (*eV*)
Sodium (Na)	0.55	2.30
Aluminium (Al)	0.99	4.18
Platinum (Pt)	1.50	6.30

[Note: The values you give as answers should be very close to the values given in the table above. Also, you could have given these values to one decimal place.]

(b) This light has a frequency greater than the threshold frequency, so photoelectrons will be emitted with a range of kinetic energies up to a maximum value.

48. The law of conservation of energy states that energy cannot be created or destroyed. However, it can be transferred, with the total amount of energy remaining the same, as in the photoelectric effect.

When a photon strikes a metallic surface, it has initial energy, $E = hf$. This energy will be passed on to any photoelectrons emitted from the surface. Some of this energy, the work function (ϕ), is required to remove the photoelectron from the surface. Any remaining energy after a photoelectron has been emitted from the metal will appear as its kinetic energy (K_{max}).

So, $hf = \phi + K_{max}$ ... i.e. $K_{max} = hf - \phi$.

49. Like a black body, the Earth absorbs radiation emitted by the Sun. However, it does not absorb all of the incident radiation as would a black body. The Earth re-radiates some of this energy, but not all of it. Hence the Earth is not a 'black body', so the description is invalid.