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# Topic 3.12: Properties of Photons

Worksheet · AP Chemistry

UNIT 3 · PROPERTIES OF SUBSTANCES AND MIXTURES

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## How to Use This Worksheet

Work in order. Section A checks the ideas: what a photon pays to free an electron, what the work function and threshold frequency mean, and what intensity does and does not control. Section B builds the calculations: maximum kinetic energy in joules and in electron volts, threshold frequencies and wavelengths, and reading the graph of KE_max against frequency. Section C combines metals, colours and experimental data in exam style.

Every value you need is stated in the question, so each question can be answered from the text alone. Where a calculation needs them, use $h = 6.626 \times 10^{-34}$ J·s, $c = 3.00 \times 10^{8}$ m/s, Avogadro's number $= 6.022 \times 10^{23}$ $mol^{-1}$ and 1 eV $= 1.602 \times 10^{-19}$ J. Convert every wavelength to metres before substituting it, and never mix joules with electron volts inside one subtraction.

Do not look at the answer key until you have attempted every question.

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## Section A: Recall and Concepts

**A1.** (a) Define a photon. (b) Define the work function of a metal. (c) Define the threshold frequency of a metal. (d) Write down the equation linking the work function, Planck's constant and the threshold frequency. (e) State two units in which a work function can be quoted.

**A2.** Bright red light shines on a metal surface and ejects no electrons. (a) State what happens if the intensity of the red light is doubled, and explain why. (b) State what happens if the red light is left shining on the metal for a much longer time, and state what a wave model of light would wrongly predict in this situation. (c) State the single change to the light that will cause electrons to be ejected.

**A3.** A beam above a metal's threshold frequency is ejecting electrons. For each change, state the effect on (i) the number of electrons ejected per second and (ii) the maximum kinetic energy of the ejected electrons. (a) The intensity is doubled at the same frequency. (b) The frequency is raised while the number of photons arriving per second is kept the same. (c) The same light is shone on a second metal that has a larger work function.

**A4.** (a) An ultraviolet photon and an infrared photon each strike a metal surface. State which is more likely to eject an electron, and explain your answer using $E = h\nu$. (b) A student claims the infrared photon should eject electrons more easily because it travels faster and hits the surface harder. Correct both errors in that claim. (c) Two photons, each carrying exactly half the work function energy, strike the same electron at the same instant. Explain why the electron is still not ejected.

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**A5.** The maximum kinetic energy of ejected electrons is plotted against the frequency of the incoming light for one metal, giving a straight line that begins partway along the frequency axis. (a) State what the slope of the line gives. (b) State what the intercept on the frequency axis gives. (c) State what the intercept on the energy axis represents. (d) Explain why the line has no points below the frequency-axis intercept. (e) Describe how the line for a metal with a larger work function compares with this one: its slope, and where it meets the frequency axis.

## Section B: Core Practice

**B1.** A metal has work function $\Phi = 3.2 \times 10^{-19}$ J. (a) Calculate its threshold frequency. (b) Calculate its threshold wavelength, in nanometres. (c) State whether green light of wavelength 500 nm can eject electrons from this metal, and justify your answer.

**B2.** Light of frequency $8.0 \times 10^{14}$ Hz strikes the metal of question B1. (a) Calculate the energy of one photon of this light. (b) Calculate the maximum kinetic energy of the ejected electrons. (c) The frequency of the light is doubled. Calculate the new maximum kinetic energy, and state by how much the maximum kinetic energy has increased.

**B3.** A metal has a work function of 1.9 eV. It is illuminated with violet light of wavelength 400 nm. (a) Convert the work function to joules. (b) Calculate the energy of one photon of the violet light, in joules and in electron volts. (c) Calculate the maximum kinetic energy of the ejected electrons, in electron volts and in joules. (d) Calculate the longest wavelength of light that can eject electrons from this metal.

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**B4.** Photons of energy 5.0 eV eject electrons from a metal, and the ejected electrons have maximum kinetic energy 1.8 eV. (a) Calculate the work function of the metal, in electron volts. (b) Convert the work function to joules, and calculate the threshold frequency of the metal. (c) State, with a calculation, whether red light of wavelength 700 nm can eject electrons from this metal.

**B5.** For one metal, a graph of maximum kinetic energy against frequency is a straight line that meets the frequency axis at $6.0 \times 10^{14}$ Hz. (a) Calculate the work function of the metal, in joules and in electron volts. (b) Calculate the maximum kinetic energy of electrons ejected from this metal by light of frequency $1.1 \times 10^{15}$ Hz. (c) State the value of the slope of the line, and state what it represents. (d) Calculate the longest wavelength of light that ejects electrons from this metal.

**B6.** A laser emits light of wavelength $6.00 \times 10^{-7}$ m. (a) Calculate the energy of one photon of this light. (b) Calculate the energy of one mole of these photons, in kJ/mol. (c) The laser shines on a metal of work function $2.5 \times 10^{-19}$ J. Calculate the maximum kinetic energy of the ejected electrons. (d) A second metal has work function $3.6 \times 10^{-19}$ J. State whether the laser can eject electrons from it if it shines for long enough, and explain your answer.

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## Section C: Exam Style

**C1.** A metal has work function $3.5 \times 10^{-19}$ J. Bright red light of wavelength 700 nm shines on the metal and ejects no electrons, while dim green light of wavelength 520 nm ejects electrons. (a) Calculate the threshold wavelength of the metal. (b) Calculate the energy of one red photon, and use your answer to explain why the bright red light ejects nothing. (c) Calculate the maximum kinetic energy of the electrons ejected by the green light. (d) The red light is made ten times as intense. State what changes, if anything. (e) The green light is made half as intense. State what happens to the number of electrons ejected per second and to their maximum kinetic energy.

**C2.** Ultraviolet light of wavelength 300 nm falls on two metals. Metal X has work function 2.2 eV and metal Y has work function 4.3 eV. (a) Calculate the energy of one photon of the ultraviolet light, in joules and in electron volts. (b) Calculate the maximum kinetic energy of the electrons ejected from metal X, in electron volts. (c) Explain why no electrons are ejected from metal Y. (d) Calculate the longest wavelength of light that can eject electrons from metal Y, and name the region of the spectrum it lies in. (e) The intensity of the ultraviolet light is doubled. State the effect on the electrons ejected from each metal.

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**C3.** In an experiment on one metal, the maximum kinetic energy of the ejected electrons is measured at four frequencies of incoming light: at $\nu = 7.0 \times 10^{14}$ Hz, $KE_{max} = 0.64 \times 10^{-19}$ J; at $\nu = 9.0 \times 10^{14}$ Hz, $KE_{max} = 1.96 \times 10^{-19}$ J; at $\nu = 1.10 \times 10^{15}$ Hz, $KE_{max} = 3.29 \times 10^{-19}$ J; and at $\nu = 1.30 \times 10^{15}$ Hz, $KE_{max} = 4.61 \times 10^{-19}$ J. (a) Calculate the gradient of the $KE_{max}$ against $\nu$ line from the first and last data points, and state what constant it measures. (b) Use the data to find the threshold frequency of the metal. (c) Calculate the work function of the metal. (d) Predict the maximum kinetic energy of electrons ejected by light of frequency $1.50 \times 10^{15}$ Hz. (e) Explain why no measurement could be made at a frequency of $5.0 \times 10^{14}$ Hz.

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## Answer Key

**A1.** (a) A photon is a discrete packet, or quantum, of electromagnetic radiation, carrying energy $E = h\nu$ set by its frequency. (b) The work function is the minimum energy needed to remove an electron from the surface of the metal. (c) The threshold frequency is the minimum frequency of light that can eject electrons from the metal: at that frequency each photon carries exactly the work function energy. (d) $\Phi = h\nu_0$. (e) Joules (J) and electron volts (eV).

**A2.** (a) Nothing changes: no electrons are ejected. Doubling the intensity doubles the number of photons arriving per second, but each red photon still carries less than the work function energy, and one photon alone must pay the full escape cost. (b) Still nothing, however long the light shines. A wave model would wrongly predict that energy delivered continuously should build up in the electron until it escapes, so dim light of any frequency should work after a delay. (c) Raise the frequency of the light (equivalently, shorten its wavelength) until each photon carries at least the work function energy.

**A3.** (a) (i) The number of electrons ejected per second doubles, because there are twice as many photons and each above-threshold photon can free one electron. (ii) The maximum kinetic energy is unchanged, because it is set by $h\nu - \Phi$ and neither has changed. (b) (i) The number per second is unchanged, because the photon arrival rate is unchanged. (ii) The maximum kinetic energy increases, because each photon now carries more energy while $\Phi$ is fixed. (c) (i) The number per second falls (and becomes zero if the photon energy drops below the new work function), because fewer, or no, photons can pay the higher escape cost. (ii) The maximum kinetic energy decreases by exactly the increase in the work function.

**A4.** (a) The ultraviolet photon. It has the higher frequency, so by $E = h\nu$ it carries more energy, and ejection depends on whether a single photon's energy reaches the work function. The infrared photon, with its lower frequency and lower energy, may fall below the work function and eject nothing. (b) Both claims are wrong. All photons travel at the same speed, c, in a vacuum, whatever their colour. And a photon does not hit harder because of any speed: what it delivers is its energy, $E = h\nu$, and the infrared photon's lower frequency makes that energy smaller, not larger. (c) Photons never pool or share their energy. Ejection is a single event in which one photon hands its whole energy to one electron; two half-price photons cannot combine to pay a full work function, so the electron stays bound.

**A5.** (a) Planck's constant, h. (b) The threshold frequency, $\nu_0$. (c) The negative of the work function, $-\Phi$: the line extrapolated back reaches $KE = -\Phi$ at zero frequency, because $\Phi$ is spent before any kinetic energy appears. (d) Below $\nu_0$ each photon carries less than the work function, so no electrons are ejected and there is no kinetic energy to plot. (e) The slope is the same, because the slope is h for every metal: the lines are parallel. The line for the larger work function meets the frequency axis further to the right, at a higher threshold frequency.

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**B1.** (a) $\nu_0 = \Phi/h = (3.2 \times 10^{-19}) \div (6.626 \times 10^{-34}) = 4.8 \times 10^{14}$ Hz. (b) $\lambda_0 = c/\nu_0 = (3.00 \times 10^{8}) \div (4.83 \times 10^{14}) = 6.21 \times 10^{-7}$ m = 621 nm. The same answer comes from $\lambda_0 = hc/\Phi$. (c) Yes. Green light at 500 nm is shorter than the 621 nm threshold wavelength, so each green photon carries more than the work function energy and electrons are ejected.

**B2.** (a) $E = h\nu = 6.626 \times 10^{-34} \times 8.0 \times 10^{14} = 5.30 \times 10^{-19}$ J. (b) KE_max $= h\nu - \Phi = 5.30 \times 10^{-19} - 3.2 \times 10^{-19} = 2.10 \times 10^{-19}$ J. (c) At $\nu = 1.6 \times 10^{15}$ Hz, $E = h\nu = 6.626 \times 10^{-34} \times 1.6 \times 10^{15} = 1.06 \times 10^{-18}$ J, so KE_max $= 1.06 \times 10^{-18} - 3.2 \times 10^{-19} = 7.40 \times 10^{-19}$ J. The increase is $7.40 \times 10^{-19} - 2.10 \times 10^{-19} = 5.30 \times 10^{-19}$ J, exactly h times the original frequency. The kinetic energy has not doubled: it has grown from 2.10 to 7.40 $\times 10^{-19}$ J, because the work function is subtracted in both cases and only the photon energy term doubled.

**B3.** (a) $\Phi = 1.9 \times 1.602 \times 10^{-19} = 3.04 \times 10^{-19}$ J. (b) $E = hc/\lambda = (6.626 \times 10^{-34} \times 3.00 \times 10^{8}) \div (4.00 \times 10^{-7}) = (1.99 \times 10^{-25}) \div (4.00 \times 10^{-7}) = 4.97 \times 10^{-19}$ J. In electron volts: $4.97 \times 10^{-19} \div 1.602 \times 10^{-19} = 3.10$ eV. (c) In electron volts: KE_max $= 3.10 - 1.9 = 1.20$ eV. In joules: KE_max $= 4.97 \times 10^{-19} - 3.04 \times 10^{-19} = 1.93 \times 10^{-19}$ J. (d) $\lambda_0 = hc/\Phi = (1.99 \times 10^{-25}) \div (3.04 \times 10^{-19}) = 6.53 \times 10^{-7}$ m, about 653 nm. Any wavelength of 653 nm or shorter ejects electrons from this metal.

**B4.** (a) $\Phi = h\nu -$ KE_max $= 5.0 - 1.8 = 3.2$ eV. (b) $\Phi = 3.2 \times 1.602 \times 10^{-19} = 5.13 \times 10^{-19}$ J. Then $\nu_0 = \Phi/h = (5.13 \times 10^{-19}) \div (6.626 \times 10^{-34}) = 7.7 \times 10^{14}$ Hz. (c) $E = hc/\lambda = (1.99 \times 10^{-25}) \div (7.00 \times 10^{-7}) = 2.84 \times 10^{-19}$ J, which is 1.77 eV. That is less than the 3.2 eV work function, so red photons cannot pay the escape cost and no electrons are ejected, at any intensity.

**B5.** (a) The intercept is the threshold frequency, so $\Phi = h\nu_0 = 6.626 \times 10^{-34} \times 6.0 \times 10^{14} = 3.98 \times 10^{-19}$ J. In electron volts: $3.98 \times 10^{-19} \div 1.602 \times 10^{-19} = 2.48$ eV. (b) KE_max $= h\nu - \Phi = (6.626 \times 10^{-34} \times 1.1 \times 10^{15}) - 3.98 \times 10^{-19} = 7.29 \times 10^{-19} - 3.98 \times 10^{-19} = 3.31 \times 10^{-19}$ J. The shortcut KE_max $= h(\nu - \nu_0) = 6.626 \times 10^{-34} \times 5.0 \times 10^{14}$ gives the same $3.31 \times 10^{-19}$ J. (c) The slope is $6.626 \times 10^{-34}$ J·s, Planck's constant: the slope of the KE_max against $\nu$ line is h for every metal. (d) $\lambda_0 = c/\nu_0 = (3.00 \times 10^{8}) \div (6.0 \times 10^{14}) = 5.00 \times 10^{-7}$ m = 500 nm.

**B6.** (a) $E = hc/\lambda = (1.99 \times 10^{-25}) \div (6.00 \times 10^{-7}) = 3.31 \times 10^{-19}$ J. (b) Per mole: $3.31 \times 10^{-19} \times 6.022 \times 10^{23} = 2.0 \times 10^{5}$ J/mol, which is $2.0 \times 10^{2}$ kJ/mol. (c) KE_max $= 3.31 \times 10^{-19} - 2.5 \times 10^{-19} = 8.1 \times 10^{-20}$ J. (d) No. Each laser photon carries $3.31 \times 10^{-19}$ J, less than this metal's $3.6 \times 10^{-19}$ J work function. Shining for longer only delivers more under-priced photons; photons never pool their energy, so no electron is ever freed.

**C1.** (a) $\lambda_0 = hc/\Phi = (1.99 \times 10^{-25}) \div (3.5 \times 10^{-19}) = 5.68 \times 10^{-7}$ m = 568 nm. Only light of 568 nm or shorter can eject electrons from this metal. (b) $E = hc/\lambda = (1.99 \times 10^{-25}) \div (7.00 \times 10^{-7}) = 2.84 \times 10^{-19}$ J. That is less than the $3.5 \times 10^{-19}$ J work function, so no single red photon can free an electron. Brightness only multiplies the number of failing photons, so nothing is ejected however bright the beam. (c) $E = hc/\lambda = (1.99 \times 10^{-25}) \div (5.20 \times 10^{-7}) = 3.82 \times 10^{-19}$ J. Then KE_max $= 3.82 \times 10^{-19} - 3.5 \times 10^{-19} = 3.2 \times 10^{-20}$ J. (d) Nothing changes: still no electrons. Ten times the intensity means ten times as many photons per second, each still below the work function. (e) Half as many photons arrive

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per second, so half as many electrons are ejected per second. The maximum kinetic energy is unchanged at $3.2 \times 10^{-20}$ J, because it is fixed by the photon energy and the work function, not by the photon count.

**C2.** (a) $E = hc/\lambda = (1.99 \times 10^{-25}) \div (3.00 \times 10^{-7}) = 6.63 \times 10^{-19}$ J. In electron volts: $6.63 \times 10^{-19} \div 1.602 \times 10^{-19} = 4.14$ eV. (b) $KE_{max} = 4.14 - 2.2 = 1.94$ eV. (c) Each photon carries 4.14 eV, which is less than metal Y's 4.3 eV work function. No photon can pay Y's escape cost, so no electrons are ejected from Y at any intensity. (d) $\Phi = 4.3 \times 1.602 \times 10^{-19} = 6.89 \times 10^{-19}$ J, so $\lambda_0 = hc/\Phi = (1.99 \times 10^{-25}) \div (6.89 \times 10^{-19}) = 2.89 \times 10^{-7}$ m, about 289 nm. That is ultraviolet, shorter than the 400 nm violet edge of visible light. (e) For metal X, twice the intensity ejects twice as many electrons per second, with the maximum kinetic energy unchanged at 1.94 eV. For metal Y, still nothing: doubling the count of photons that each fall short changes nothing.

**C3.** (a) Gradient $= (4.61 \times 10^{-19} - 0.64 \times 10^{-19}) \div (1.30 \times 10^{15} - 7.0 \times 10^{14}) = (3.97 \times 10^{-19}) \div (6.0 \times 10^{14}) = 6.6 \times 10^{-34}$ J·s. That is Planck's constant, h. (b) Work back from the first point: the line reaches KE = 0 at $\nu_0 = 7.0 \times 10^{14} - (0.64 \times 10^{-19} \div 6.626 \times 10^{-34}) = 7.0 \times 10^{14} - 0.97 \times 10^{14} \approx 6.0 \times 10^{14}$ Hz. (c) $\Phi = h\nu_0 = 6.626 \times 10^{-34} \times 6.04 \times 10^{14} = 4.0 \times 10^{-19}$ J. The same value comes from any data point: at $\nu = 9.0 \times 10^{14}$ Hz, $\Phi = h\nu - KE_{max} = 5.96 \times 10^{-19} - 1.96 \times 10^{-19} = 4.0 \times 10^{-19}$ J. (d) $KE_{max} = h\nu - \Phi = (6.626 \times 10^{-34} \times 1.50 \times 10^{15}) - 4.0 \times 10^{-19} = 9.94 \times 10^{-19} - 4.0 \times 10^{-19} = 5.94 \times 10^{-19}$ J. (e) At $5.0 \times 10^{14}$ Hz each photon carries $h\nu = 3.31 \times 10^{-19}$ J, less than the $4.0 \times 10^{-19}$ J work function. The frequency is below threshold, so no electrons are ejected and there is no kinetic energy to measure.

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