Chapter 27

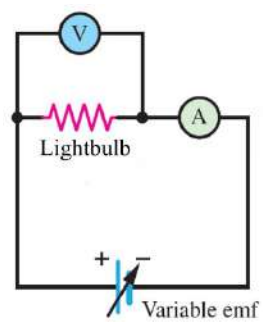
Quantum Optics

27.1 Black body radiation

OALG 27.1.1 Observe and explain

Your friend Audrey wants to investigate how the power emitted by a hot object depends on the temperature of the object. She learned that tungsten is the metal that has highest melting point. Therefore, she decides to use the tungsten filament in the lightbulb of an overhead projector as the emitting object in her experiments (see the figure on the right; note: the filament is flat, not cylindrical).

Audrey obtains a tungsten filament lightbulb, an ammeter, a voltmeter and a variable voltage DC power supply. She connects these elements as shown in the next figure on the right and measures the current I through the lightbulb at different values of the potential difference ΔV across the lightbulb (columns 1 and 2 in the table below). Using these data, she calculates the resistance of the filament R_{filament} and the power output of the light bulb P for each measurement (columns 3 and 4).



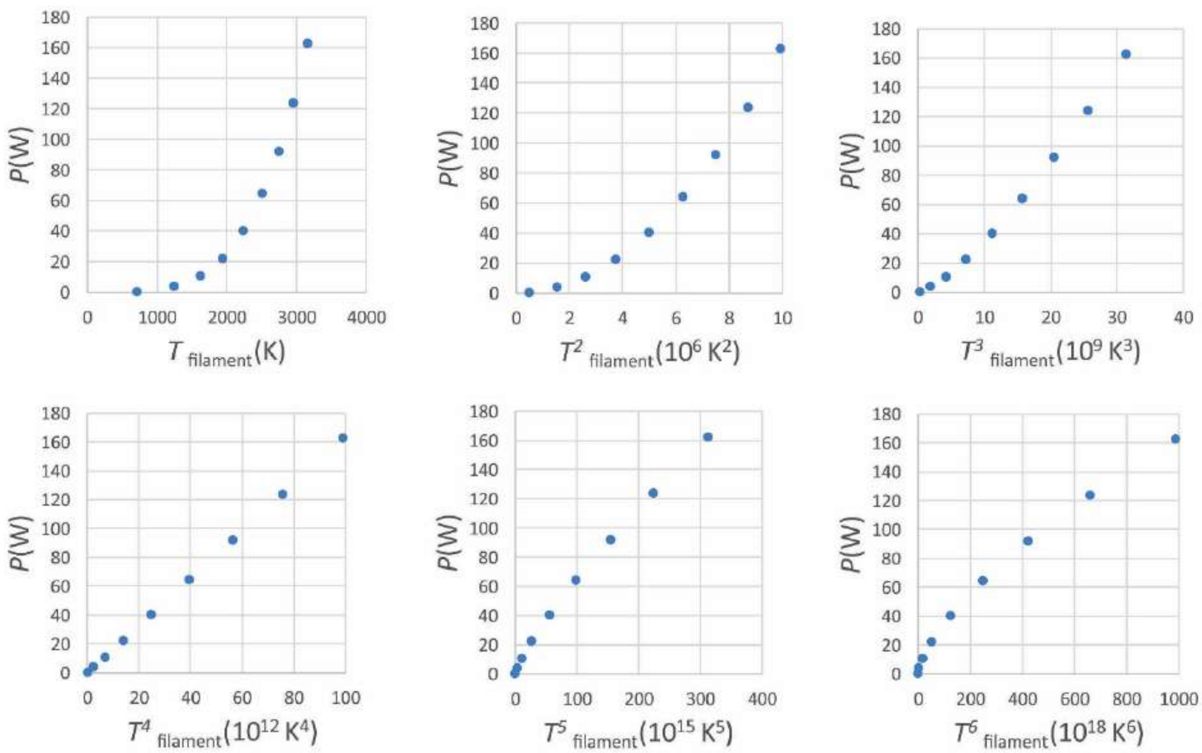
On the Internet, she finds the following empirical expression that relates the approximate temperature of the tungsten wire with the ratio $R / R_{300\text{ K}}$, where R is the resistance of the wire at temperature T, and $R_{300\text{ K}}$ is the resistance of the wire at about 300 K (room temperature):

$$T = [(175.49\text{ K})/\Omega] \times R + 207.27\text{ K}$$

Learning this, she comes up with an idea to use this relationship to estimate the temperature of the tungsten filament in her experiments. Using an ohmmeter, she measures the resistance of the lightbulb filament at room temperature, $R_{300\text{ K}} = 0.120\ \Omega$. She writes the ratios $R/R_{300\text{ K}}$ and corresponding estimated temperatures of the tungsten filament in columns 5 and 6.

(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
ΔV(V)	I(A)	$R_{\text{filament}}(\Omega)$	P(W)	$R_{\text{filament}} / R_{300\text{ K}}$	T_{filament}(K)
0.35	1.02	0.34	0.4	2.86	710
1.66	2.34	0.71	3.9	5.91	1248
3.20	3.32	0.96	10.6	8.03	1621
5.12	4.35	1.18	22.3	9.81	1934
7.46	5.40	1.38	40.3	11.51	2235
10.04	6.41	1.57	64.4	13.05	2506
12.60	7.30	1.73	92.0	14.38	2740
15.22	8.14	1.87	123.9	15.58	2952
18.08	9.00	2.01	162.7	16.74	3156

After collecting and calculating all these data, she decides to test several mathematical models for the relationship $P(T_{\text{filament}})$, which she is seeking. Using data from the table she draws six graphs, each for a different power-law relationship between P and T_{filament}:



a. Explain how Audrey determined the values in columns 3 and 4 and which physical laws or definitions she used. Which assumptions did Audrey need to make to attribute the values in column 3 to the resistance of the filament?

b. You learned in Chapter 19 that the resistance of a metal increases with increasing temperature. Is the empirical equation for tungsten above consistent with this property of metals? Explain and provide quantitative arguments.

c. Based on the graphs shown above, write the mathematical model (a function) that best describes the P-versus-T_{filament} relationship.

d. Discuss under which assumptions the model that you suggested in part **c**, describes the relationship between the power emitted by the bulb in the form of electromagnetic waves and the temperature of the bulb's filament.

e. Read and interrogate Section 27.1 in the textbook and then estimate the surface area of the filament in the bulb used in the experiments above. Evaluate the result.

f. Go to https://phet.colorado.edu/sims/html/blackbody-spectrum/latest/blackbody-spectrum_en.html and investigate whether the simulation correctly represents Wien's law and Stephan-Boltzmann's law. Explain with data how you came to your conclusion.

OALG 27.1.2 Practice

Answer Questions 1, 2, 3 on page 876 and solve Problems 3-6 on page 877 and Problem 42 on page 878 in the textbook.

27.2 Photoelectric effect

OALG 27.2.1 Observe and explain

Watch the video at [https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-27-2-1].

Watch the experimenter touch the metal plate on the top of an electroscope with differently charged bars and rub them against the plate. Rubbing is necessary to "transfer" charge from the charged object to the electroscope. Note what happens to the electroscope leaves in each case. Work with your neighbors to come up with an explanation for the outcome of each experiment.

The experiment	**Outcome of experiment**	**Explanation**
a. Rub the metal plate with a negatively charged PVC bar. Then remove the bar. (The PVC bar is charged negatively if rubbed with wool.)	The leaves remain deflected for a long time.	
b. Rub the metal plate with a positively charged acrylic bar. Then remove the bar. (The acrylic bar is charged positively if rubbed with wool.)	The leaves remain deflected for a long time.	
c. Rub the metal plate with a negatively charged PVC bar. Then remove the bar. Then shine a flashlight on the metal plate.	The leaves remain deflected for a long time.	
d. Rub the metal plate with a negatively charged PVC bar. Then remove the bar. Then shine an ultraviolet (UV) light on the metal plate.	The electroscope discharges (as indicated by the leaves moving together).	
e. Repeat experiments **c**. and **d**., only this time use a positively charged acrylic bar.	The leaves remain deflected for a long time.	

f. Compare your explanations to the explanations on page 855 in the textbook.

The discharge of the negatively charged electroscope due to exposure to light is called the *photoelectric effect.*

OALG 27.2.2 Explain

In the previous activity you found that shining UV light on a negatively charged electroscope discharges it. Shining white light does not produce this effect. Shining UV light on a positively charged electroscope does not produce the effect either. Your goal is to use the knowledge of the electromagnetic wave model of light to explain these patterns. Below are two assumptions that you can use.

Assume that free electrons inside metals can move and positively charged ions cannot.

Assume that light is an electromagnetic wave in which $\vec{E}$ and $\vec{B}$ fields oscillate periodically.

a. Use your knowledge of the effects of the electric field on charged particles to explain the effect of the UV light on the negatively charged metal surface in Activity 27.2.1 parts **c**. and **d**. (think microscopically).

b. Repeat for Activity 27.2.1 part **e**.

OALG 27.2.3 Test your explanations

a. Think of what experiments you could design to test your explanations of the patterns from Activity 27.2.1. Make predictions of the outcomes of these experiments based on the explanations under test.

b. We videoed a series of experiments that could test your explanations. Once you are done with part **a** watch the experiments in the order of appearance (https://youtu.be/eKhZoCrG0C8,

https://youtu.be/8hGBUeszdCE, https://youtu.be/bwGF-gIqLPY) and discuss whether and how you could have predicted their outcomes using your explanations. If you could not predict their outcomes, examine your additional assumptions and then the explanations. What explanations couldn't you reject? Note, that the third video is a continuation of the second one. It is a testing experiment for sign of charges on the electroscopes at the end of the second experiment.

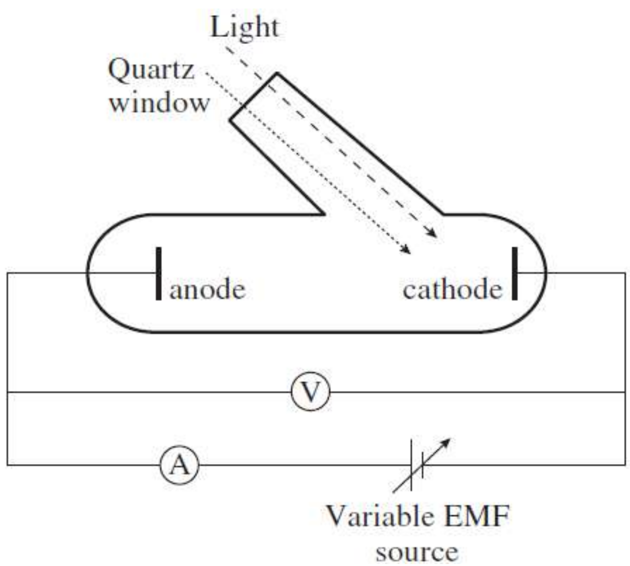
OALG 27.2.4 Explain

You observed in Activity 27.2.1 that visible light does not discharge a negatively charged electroscope. The increase of the intensity of visible light does not make a difference—no current is observed. However, even at very low intensity, UV light discharges a negatively charged electroscope. How can you explain this pattern using the model of light as an electromagnetic wave? Remember, the energy of an electromagnetic wave depends only on the amplitude of an E or B field.

OALG 27.2.5 Observe and explain

Physicists use an evacuated glass container such as the one shown below to study the photoelectric effect. Light of different frequencies can shine through a quartz window onto a metal plate connected to the negative pole of the battery. Such a plate is called the *cathode*. The other plate inside the tube is connected to the positive side of the battery and is called the *anode*. In our experiments the anode and the cathode are always made of the same material. When no UV light shines on the cathode, the ammeter does not register any current. Go to https://phet.colorado.edu/sims/cheerpj/photoelectric/latest/photoelectric.html?simulation=photoelectric, play with the simulations to find as many patterns as you can and record them below:

a. List all the patterns that you found in the simulation (make sure you change the emf of the battery, the material of the cathode, the color of light and the intensity of light).



b. Use the simulation to observe that a UV light shines on the sodium cathode, the ammeter registers a current in the circuit independently of the intensity. How can you explain how UV light can cause the current? *Note*: A voltmeter has very high electrical resistance.

c. Use the simulation to observe that when the emf of the battery is zero, but the UV light still shines on the cathode, the ammeter registers a small current—much smaller than in part **a**. How can you explain it?

c. Use the simulation to observe that when the polarity of the battery is reversed, the plate on which the light shines is at a higher potential than the plate on the left side. When this reversed potential difference reaches a certain value, the ammeter reading drops to zero. Can you explain why? (This potential difference is called a *stopping potential*, V_s.)

OALG 27.2.6 Observe and explain

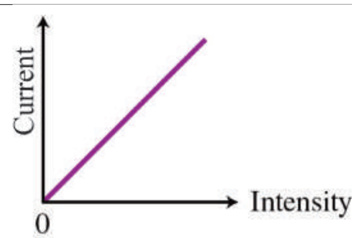
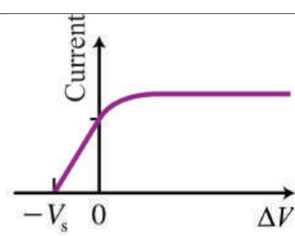
Referring to the apparatus in Activity 27.2.5, the current is stopped when the metal cathode on which the light shines is at a positive potential relative to the more negative potential of the plate on the left side.

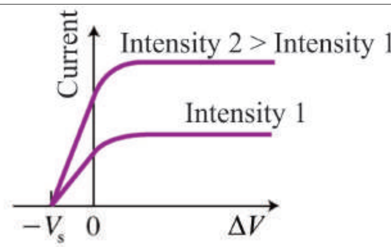
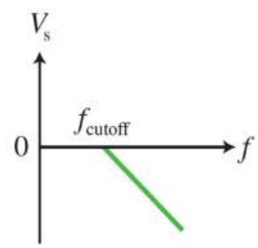
a. Surprisingly, you find that the potential difference that stops the current (see Activity 26.2.5 part **c**.) does *not* depend on the intensity of light. The electric current induced by high-intensity light is stopped as easily as electric current induced by low-intensity light. Can you explain this observation using the electromagnetic wave model of light?

b. While the stopping potential does not depend on the intensity of light, it does depend on the color: the higher the light frequency (UV versus visible, violet versus red), the higher the stopping potential. Can you explain this observation using the electromagnetic wave model of light?

OALG 27.2.7 Observe and explain

In the table below try to use the *electromagnetic wave model* of light to explain each of the experimental results involving the apparatus shown in Activity 27.2.5.

Experiment	**Result**	**Explain using the wave model**
a. As the light intensity increases, the electric current changes as shown in the graph.		
b. The dependence of the electric current on the potential difference across the electrodes is shown. Explain the steady part of the graph. The intensity of light remains constant during the experiment.	 Note: ΔV is positive when the	

	right metal plate (the cathode) connects to the positive battery terminal.	
c. Use the wave model to try to explain why the current decreases to zero when there is a negative stopping potential difference $-V_s$ in experiment **b**.		
d. You repeat the previous experiment for increasing intensity light. The stopping potential difference $-V_s$ does not change.		
e. The potential difference $-V_s$ needed to stop the electric current depends on the light frequency—see the graph.		

d. Compare your explanations to the explanations on page 857 in the textbook. How are they the same? How are they different?

OALG 27.2.8 Practice

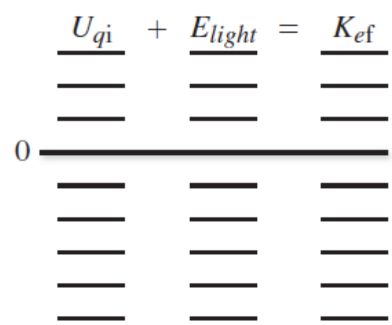
Answer Question 4 on page 876 in the textbook.

27.3 Quantum model explanation of the photoelectric effect

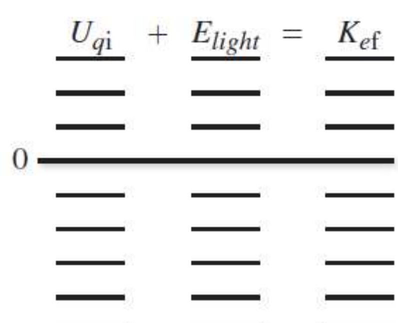
OALG 27.3.1 Represent and reason

Analyze and represent the following two historical findings:

a. In 1902 the German physicist Phillip Lenard suggested an explanation for the photoelectric effect. He proposed that light, being an electromagnetic wave, knocked out electrons from the surface of the cathode by continuously exerting force on the electrons. These electrons were then accelerated by the electric field of the battery inside the glass tube, reached the opposite electrode and closed the circuit. He reasoned that if the energy of interaction between electrons and the lattice is negative and equal to $-\phi$, and light had the energy E_{light} larger than ϕ, then the leftover energy of light would be given to the electrons in the form of kinetic energy K_{f}. Draw a new energy bar chart that represents this energy exchange process between light and electron-lattice system during the photoelectric effect. Remember that light energy is continuously coming toward the cathode, therefore the bar for light energy is continuously growing.



b. In 1905 Albert Einstein suggested that the photoelectric effect can be explained assuming that light is a stream of bundles of energy (photons), which are individually absorbed by electrons in the metals. The energy of each photon is determined by the frequency of light ($E = hf$, where $h = 6.63\times10^{-34}\,\text{J}\cdot\text{s}$); the higher the frequency, the higher the photon energy. An electron is bound to the crystal lattice, and the energy of the interaction of one electron with the lattice is $-\phi$. An electron can absorb only the energy of one photon. Draw a new energy bar chart that represents the energy exchange process between a photon and an electron-lattice during the photoelectric effect, with the initial state the electron being in the metal and the final state it being outside the metal.

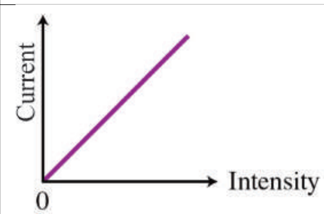
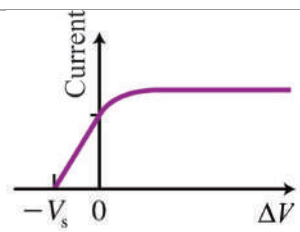


c. What are the fundamental differences between two explanations and whether each of them accounts for all observational evidence collected for photoelectric effect.

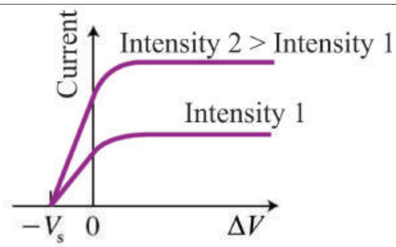
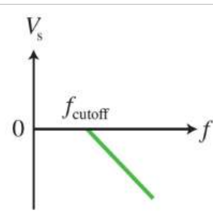
d. Read and interrogate Section 27.3 in the textbook.

27.3.2 Observe and explain

Use the photon model to try to explain the results of the five experiments in Activity 27.2.7. Before starting, carefully describe the new model.

Experiment	**Result**	**Explain using the photon model.**
a. As the light intensity increases, the electric current changes as shown in the graph.		
b. The dependence of the electric current on the potential difference across the electrodes is shown (measured by the voltmeter) while the intensity of light remains constant. Explain the steady part of the graph.	 Note: ΔV is positive when the right metal plate (the cathode) connects to the positive battery terminal.	

See next page.

Experiment	**Result**	**Explain using the photon model.**
c. Use the photon model to explain why the current decreases to zero when there is a negative stopping potential difference $-V_s$ in experiment **b**.		
d. You repeat the previous experiment for increasing intensity light. The stopping potential difference $-V_s$ does not change.		
e. The potential difference $-V_s$ needed to stop the electric current depends on the light frequency—see the graph.		

OALG 27.3.4 Observe and explain

Watch experiments in the following videos and for each experiment:

a. Describe in detail what you observe.

b. Explain what you observe in each experiment using the photon model of photoelectric effect. For help review what a neon bulb is and how it works in Section 19.2 in the textbook.

Experiment 1

https://youtu.be/MUXVOou_uhk

Experiment 2

https://youtu.be/9jU1WQRtEEI

OALG 27.3.5 Practice

Answer Questions 5 and 9 on page 876 and solve Problems 10, 12, 14, and 15 on page 877.

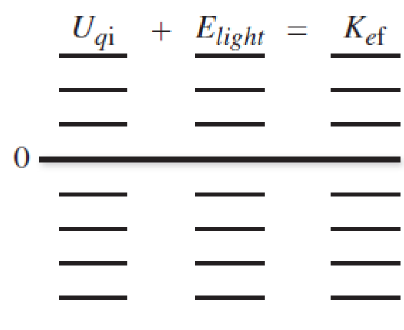
27.4 Photons

OALG 27.4.1 Read and interrogate

Read and interrogate Section 27.4 in the textbook and answer Review Question 27.4.

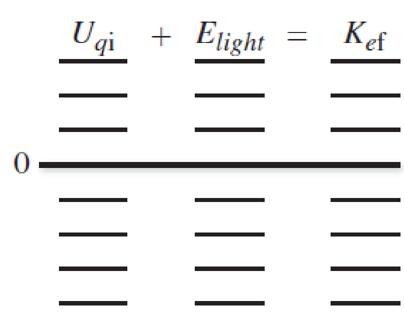
OALG 27.4.2 Represent and reason

Draw an energy bar chart to represent the following process: a photon of light hits a metal. The energy of the photon is exactly equal to the magnitude of the negative electric potential energy of the interaction between the electron and the lattice.



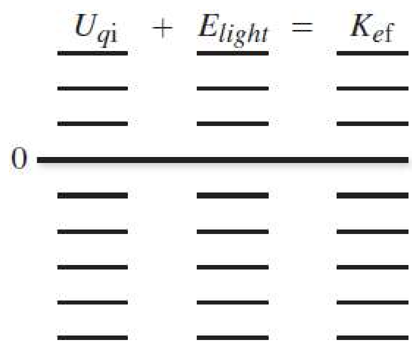
OALG 27.4.3 Represent and reason

Draw an energy bar chart to represent the following process: a photon of light hits a metal and ejects an electron with zero kinetic energy.



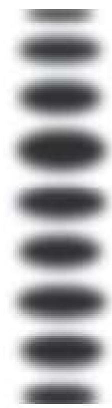
OALG 27.4.4 Represent and reason

Draw an energy bar chart to represent the following process: a photon of light hits a metal and ejects a fast-moving electron.



OALG 27.4.5 Test your ideas

Light passes through double slits and illuminates a screen producing the double-slit interference pattern (shown on the right) observed and explained in Chapter 24 using a wave model of light. However, we now have experiments that can only be explained if we consider light to be a stream of photons—a photon model for light.



a. First use the wave model of light to predict what you expect to observe on the screen if you illuminate the double slits with very low intensity light. Then use the photon model of light to make a prediction.

b. Reconcile these two models of light with the outcome of this experiment, which is described in the textbook in Testing Experiment Table 27.7.

OALG 27.4.6 Evaluate

Your friend Snehal says that the photon model of light is not a new model, but just an old particle-bullet model of light. How can you convince Snehal that his opinion is not correct?

OALG 27.4.7 Derive

We found that light exhibits a particle-like behavior when interacting with matter. If a photon has particle-like properties, it should have momentum.

a. Write an expression for the energy of a photon and set it equal to the relativistic energy of a particle with mass m moving at speed c. (Massive particles do not move at the speed of light, c. Here we are assuming that the photon is a particle moving at speed c.) Use this to determine an expression for the equivalent mass of a photon.

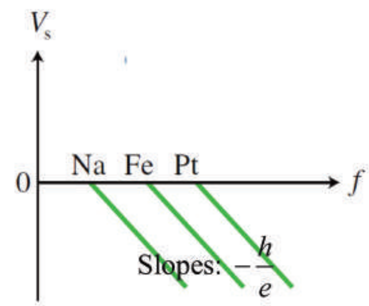
b. Write an expression for the momentum of a photon—it moves at speed *c* and has the equivalent mass *m* derived in part **a**. You should now have an expression for the momentum of a photon in terms of its frequency.

c. Rewrite this expression in terms of the wavelength of the photon.

d. Compare a photon to a classical particle—such as a billiard ball. What are the properties that are similar? What are the properties that are different?

OALG 27.4.8 Observe and explain

The experiment described in Activity 27.3.2 part **e**. is repeated for different types of metal (both the cathode and anode are made of the same metal). The results are shown below. The work functions of several metals are given in the table below. Use the photon model of light to explain these observations.



Metal	Aluminum (Al)	Copper (Cu)	Iron (Fe)	Sodium (Na)	Platinum (Pt)	Zinc (Zn)
Work function (eV)	4.1	4.7	4.7	2.3	6.4	4.3

OALG 27.4.9 Represent and reason

A 200-nm light source shines on a sodium surface. Represent with a bar chart and an equation each of the processes described below.

a. The process starts with a 200-nm photon and ends just after the ejection from sodium of an electron that moves at maximum speed.

b. The same as above, only now the electron has traveled across the photoelectric tube. A potential difference has stopped the electron just before reaching the metal collector electrode.

OALG 27.4.10 Represent and reason:

Draw an energy bar chart for each of the three photoelectric effect processes described below. Then write a mathematical description for each process (if it can occur).

a. The process starts with a photon whose energy is $hf > \phi$ and ends just after the ejection of an electron from a metal surface. Assume the electron moves at maximum possible speed.

b. The same as above only now the energy of the photon is $hf = \phi$.

c. The same as above only now the energy of the photon is $hf < \phi$.

OALG 27.4.11 Practice

Answer Questions 7, 8, and 10 – 12 on page 876 and solve Problems 21-25 on page 877 in the textbook.

27.6 Photocells, solar cells and LEDs

OALG 27.6.1 Observe and explain

In the following video https://youtu.be/caS_ZtH8Sb8 you observe a red LED connected to a voltmeter in a bright room. There is no battery connected to the LED.

a. Record your observations (the reading of the voltmeter).

b. Devise an explanation or explanations for a non-zero reading of the voltmeter although it is not connected to a battery.

c. Use your explanation to predict what will happen to the reading of the voltmeter when you bring the LED close to a lightbulb that is on. Record your prediction. Then observe the experiment https://youtu.be/QqHNoxZCvvk and compare the outcome to your prediction. Do you need to revise the explanation you constructed in part **b**?

OALG 27.6.3 Apply

a. We investigated how the color of light and the intensity of light incident on an LED (detector) affect the voltage across that LED. Specifically, when you shone red LED (source) on a red LED (detector), green LED on a red LED, red LED on a green LED, and green LED on a green LED (in every case the LED on which the light is shining is connected to a voltmeter) keeping the relative orientation (incidence angle) of the source-LED with respect to the detector-LED such that we recorded the maximum voltmeter reading.

b. Our findings are presented in the table below. Explain the differences in the voltmeter readings for four different experiments.

		Detector LED	
		Red	**Green**
Source LED	**Red**	1.60 V	0 V
	Green	1.52 V	1.78 V

OALG 27.6.4 Observe and explain

a. In the following photos you can see different non-glowing LEDs with a magnifying glass and under a microscope.

b. Explain why the image of the interior parts of the LED is highly distorted.

27.6.5 Test your ideas

Design an experiment to test your explanation from the previous activity of why the image of the interior parts of the LED is distorted and come up with a method to see inside the plastic dome clearly. *Hint*: think about the refractive index of plastic. After you have come up with the method, watch the video [https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-27-6-5] and compare your idea with the one shown in the video.

27.6.6 Explain and test your ideas

a. Observe the inside of an LED while it is glowing (after "canceling out" the plastic dome effect) – see the video [https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-27-6-6a]. Draw a detailed picture of what you see.

b. Consider a possible explanation: there might be a metal inside.

c. Come up with a way to rule out the metal-based explanation using the knowledge of LEDs that you already have (see Chapter 19). After you have come up with the idea, watch the video [https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-27-6-6b] and compare your idea with the one shown in the video.

27.6.7. Read and interrogate

Read and interrogate Section 27.6 in the textbook.

a. Explain how an LED produces light when it is connected to a circuit.

b. Explain why an LED has an opening voltage.

c. Explain how an LED can work as a small solar cell when connected to a voltmeter.

OALG 27.6.8 Practice

Solve Problems 41, 44, and 45 on page 878 in the textbook.