Quantum Optics Workshop

Eugenia Etkina and Gorazd Planinsic

Workshop materials

ALG Chapter 27 Third edition.docx

All materials are at

January 2025 Quantum Optics workshop

Please rename yourself:

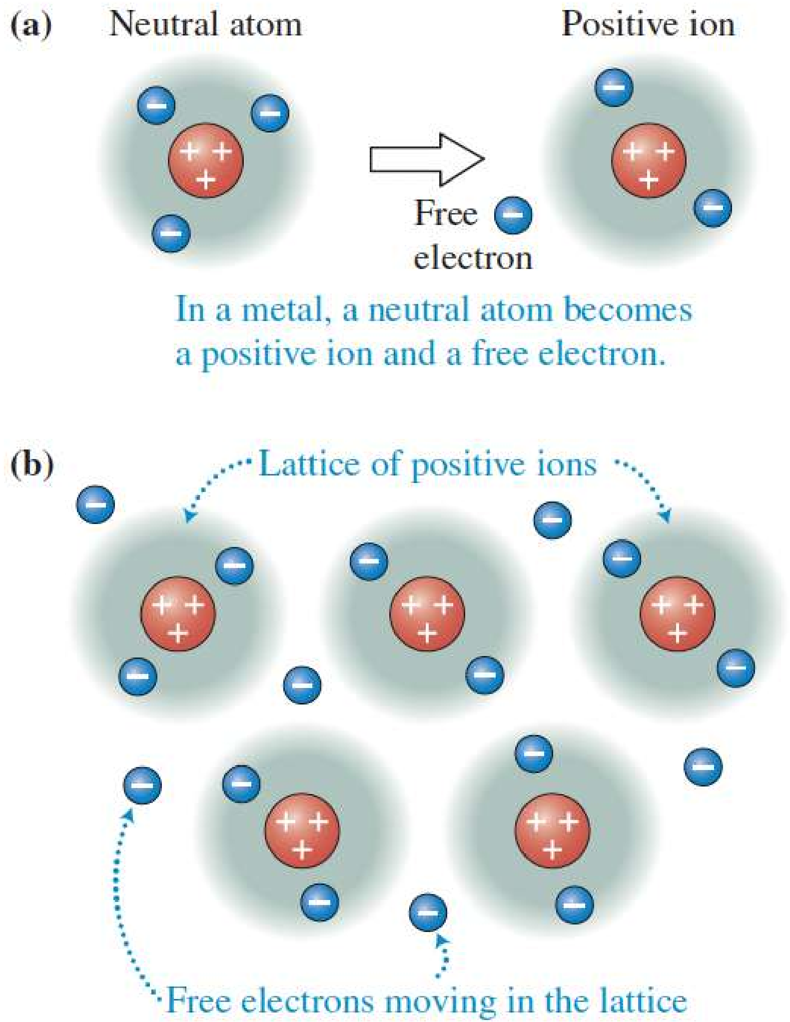
First name, High School of College, Country

Eugenia University USA

What should students know before starting this topic

1. Electric charge, force, electroscope (chapter 17)
2. Air is an insulator but it made of particles that can be ionized (chapter 17)
3. Metals are made of a crystal lattice and free electrons (Chapter 17 and 19)
4. E field as a quantity characterizing electric field and B field as a quantity characterizing magnetic field (Chapters 19 and 20)
5. Light can be modeled as an electromagnetic wave (Chapters 21 and 25)
6. In the wave electric and magnetic fields oscillate and electric field exerts an electric force on nearby charged particles. (Chapter 25)
7. Black body radiation patterns can only be explained if one assumes that light is emitted by energy portions not continuously (Chapter 17 Section 1)

Reminder:
the structure of metals



The following set of activities is in the new edition of the ALG: ALG 27.2.1

ALG Chapter 27 Third edition.docx

Watch the following experiment https://youtu.be/X7EQJU9bxV4

a.

1. Rub the metal plate with a negatively charged bar. Then remove the bar. The leaves remain deflected for a long time.

Explanation

2. Rub the metal plate with a negatively charged bar. Then remove the bar. Then shine a flashlight on the metal plate.

The leaves remain deflected for a long time.

Explanation

3. Rub the metal plate with a negatively charged 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).

Explanation

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

b. Two students who observed the same set of experiments came up with the following explanation: UV light consists of vibrating electric and magnetic fields. The electric field exerts a force on the electric charges in atoms of the air, ionizes air and ionized air is a conductor. That is why the electroscope discharges. Design an experiment that they can perform to test this explanation.

The students decided to shine UV light on a positively charged electroscope. If their hypothesis is correct, the electroscope should discharge too.

d. Watch the outcome and compare it to the prediction:
https://youtu.be/EgxVXOnsFx0

e. Now that they have rejected the ionized air explanation, the students came up with a new explanation: Maybe UV light kicks electrons out of the zinc plate? They even came up with an experiment to test it! They decided to shine UV on a neutral electroscope. Why would they do that and what prediction did they make before they performed the experiment?

f. Now they performed the experiment https://www.youtube.com/watch?v=eKhZoCrG0C8 Did the outcome match their prediction?

g. Rather disappointed they started thinking why their experiment did not match the prediction. They started thinking what they knew about the structure of metals. How does their knowledge about the structure of metals might help them explain why their experiment did not turn out as expected?

i. Luckily, their teacher helped them and ran the following experiment: https://youtu.be/8hGBUeszdCE

Explain why the teacher did this experiment and what could the students conclude from it?

j. Think of how you can test that the neutral electroscope was really charged positively by the UV light.

k. Compare your ideas for the experiment with the one we recorded.
https://youtu.be/bwGF-gIqLPY

Team 1 ALG27.2.2

Assume you know that free electrons inside metals can move and positively charged ions cannot. Assume that light is an electromagnetic wave in which electric and magnetic fields oscillate periodically.

Use your knowledge of the effects of the electric field on charged particles to explain the effect of the light on the negatively and positively charged metal surface in Activity 27.2.1.

An electric force, caused by the electric field, is exerted on the free electrons in metal (electroscope bar), which produces work (increases their energy), instead the positive ions can not be displaced. Work provides KE to the electron. If that energy is greater than the energy threshold, the electron can leave the metal. The UV light has more energy than visible light, due to a greater frequency.

Team 2 ALG 27.2.2

Assume you know that free electrons inside metals can move and positively charged ions cannot. Assume that light is an electromagnetic wave in which electric and magnetic fields oscillate periodically.

Use your knowledge of the effects of the electric field on charged particles to explain the effect of the light on the negatively and positively charged metal surface in Activity 27.2.1.

*Somehow electric field will push/pull electrons, only if the field is strong enough. Maybe UV light has strong electric field.

*UV light wave has high energy to move electrons.

Team 3 ALG 27.2.2

Assume you know that free electrons inside metals can move and positively charged ions cannot. Assume that light is an electromagnetic wave in which electric and magnetic fields oscillate periodically.

Use your knowledge of the effects of the electric field on charged particles to explain the effect of the light on the negatively and positively charged metal surface in Activity 27.2.1.

positive and negative move with or opposite E field

gain energy "naturally" or need push to go up hill

Team 4 ALG 27.2.2

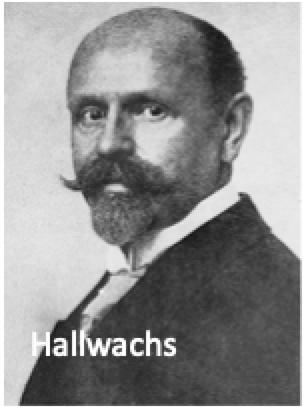
Assume you know that free electrons inside metals can move and positively charged ions cannot. Assume that light is an electromagnetic wave in which electric and magnetic fields oscillate periodically.

Use your knowledge of the effects of the electric field on charged particles to explain the effect of the light on the negatively and positively charged metal surface in Activity 27.2.1.

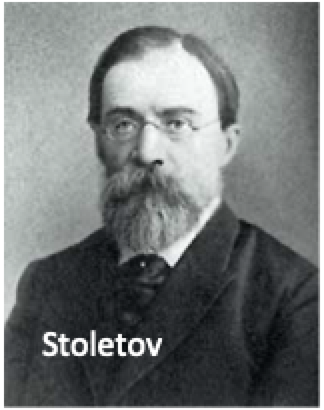
The waves from the light causes the electrons to start to resonate. So a particular matching frequency will cause this to violently rip away after some time. Otherwise the positive charges will continue to hold the negative charges there.

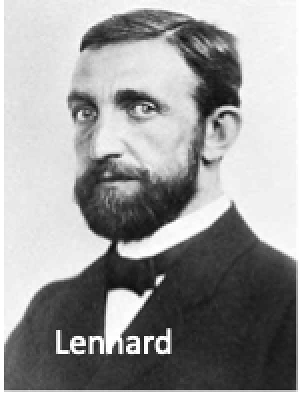
History of science: Photoelectric effect

Accidental observation



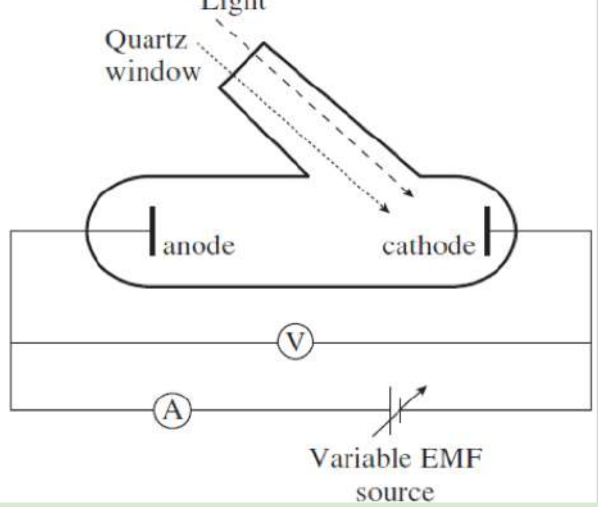
Qualitative observational experiments





Quantitative observational experiments and explanations

Team 1 ALG 27.2.3



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. Work with your group members to answer the following questions.

a. When a UV light shines on the cathode, the ammeter registers a current in the circuit. Explain how UV light can cause the current. *Note*: A voltmeter has very high electrical resistance.

Free electrons will be released by the cathode and could have enough kinetic energy (with UV light) to reach the anode, which attracts electrons.

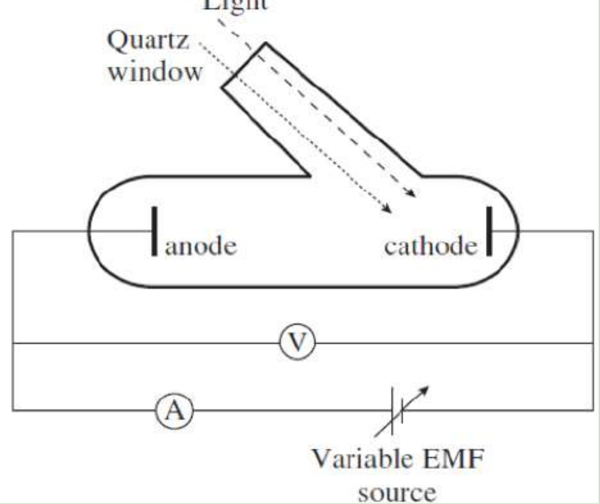
b. When the battery is replaced with a wire but the UV light still shines on the cathode, the ammeter registers a small current—much smaller than in part **a**. Explain.

Without attraction from anode, less electrons will be able to reach the other side because without the battery, the Coulomb force is smaller.

c. If the polarity of the battery is reversed, then 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. Explain why. (This potential difference is called a *stopping potential*,)

With polarity reversed, the force of the electric field on electron is directed to the cathode,and at a certain point the electric potential (multiplied for e) is equal to the maximum kinetic energy of electrons

Team 2 ALG 27.2.3



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Anode attracts electrons

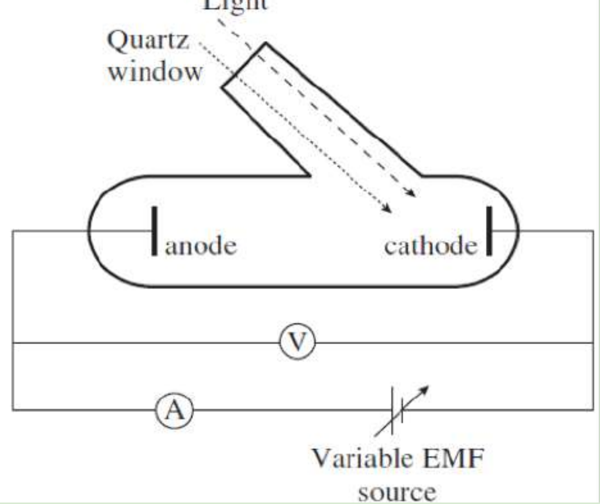
b. When the battery is replaced with a wire but the UV light still shines on the cathode, the ammeter registers a small current—much smaller than in part **a**. Explain.

Less electrons are attracted

c. If the polarity of the battery is reversed, then 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. Explain why. (This potential difference is called a *stopping potential*,)

Anode attracts electrons

Team 3 ALG 27.2.3



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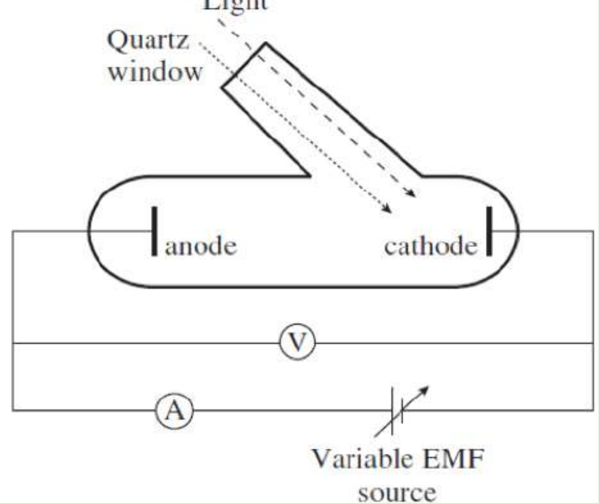
b. When the battery is replaced with a wire but the UV light still shines on the cathode, the ammeter registers a small current—much smaller than in part **a**. Explain.

Without the battery, the

c. If the polarity of the battery is reversed, then 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. Explain why. (This potential difference is called a *stopping potential*,)

Team 4 ALG 27.2.3



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a. When a UV light shines on the cathode, the ammeter registers a current in the circuit. Explain how UV light can cause the current. *Note*: A voltmeter has very high electrical resistance.

Current is a flow of electrons, so electrons flow from cathode to anode. UV light liberates the electrons put depositing energy "somehow"! Electrons are attracted to the + anode and that causes a net flow and current.

b. When the battery is replaced with a wire but the UV light still shines on the cathode, the ammeter registers a small current—much smaller than in part **a**. Explain.

When there was no additional electric field, there is no force pulling the electrons towards the anode. The only electrons that complete the circuit are the ones that happened to leave the cathode already moving in the direction of the anode.

c. If the polarity of the battery is reversed, then 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. Explain why. (This potential difference is called a *stopping potential*,)

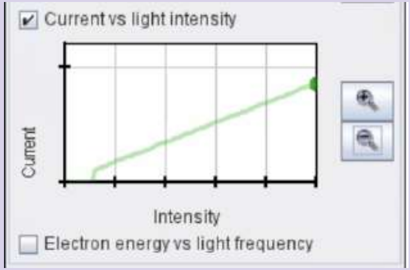
The "cathode" end would be positive. When electrons are kicked off using UV, the electrons would immediately be pulled back to this "cathode." Thus, no electrons would pass across the vacuum to the "anode" creating a flow of electrons.

In the next activity you will work with a PHET simulation. You will need to obtain several graphs. When you get a desired graph, take a screenshot and paste it into the slide for your team. I created two slides for every team as there are 5 experiments. If you need additional slides, please add them but try not to delete any slides. Be very careful with that.

Team 1 ALG 27.2.4 ALG Chapter 27 Third edition.docx

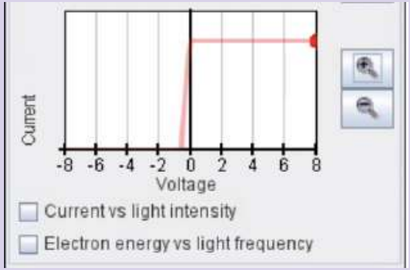
Experiment 1: Observed result

wavelength: 403nm, with more intensity, we have more current (because more electrons are released from the plate. EE: But why are more electrons released from the plate>



Explanation: **As long we have enough energy to release electrons, then the more light that is shining on the plate the more electrons will be released.**

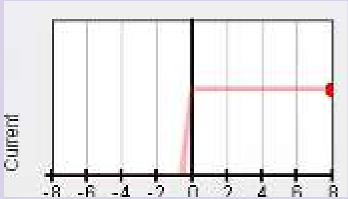
Experiment 2: **Observed result, now when the polarity of the battery is reversed to a certain negative value, now the electrons are not reaching the other plate.**



Explanation because the electrons don't have enough energy. That is the "stopping potential". Once the electrons have reached a certain energy, the magnitude of positive value is not needed anymore, so even if V battery = 0, the electrons are still moving.The number of electrons depend only on light intensity, so the current does not depend on the voltage.

Team 1 ALG 27.2.4 [ALG Chapter 27 Third edition.docx]

Experiment 3: Observed result



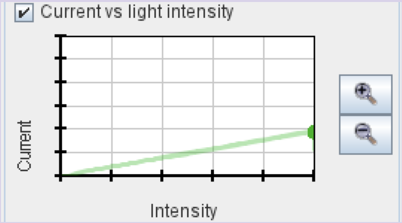
Explanation:

Experiment 4: Observed result

Explanation

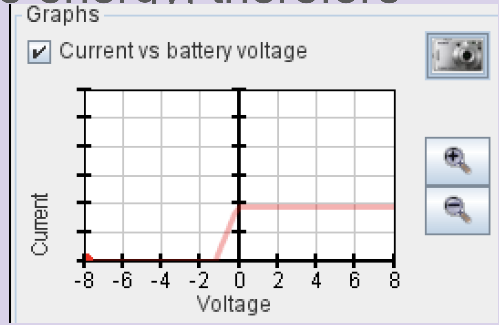
Experiment 5 Explanation

Team 2 ALG 27.2.4 ALG Chapter 27 Third edition.docx



Experiment 1: Observed result

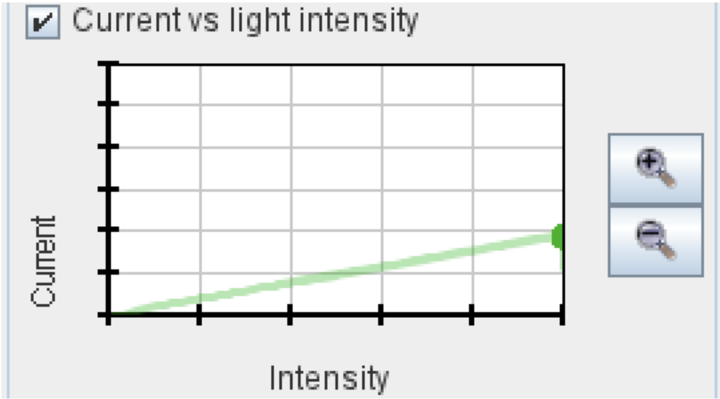
Explanation: more intensity means a greater amplitude, more energy, therefore more electrons ejected making a higher current

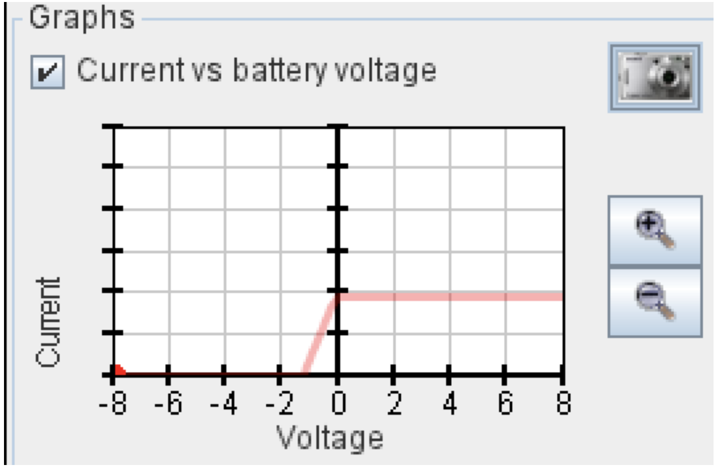


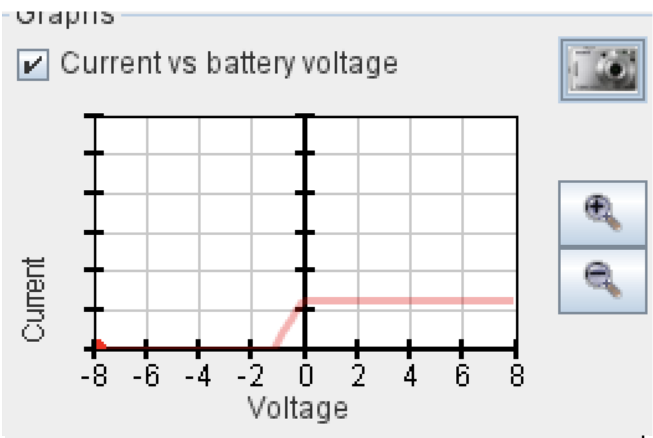
Experiment 2: Observed result

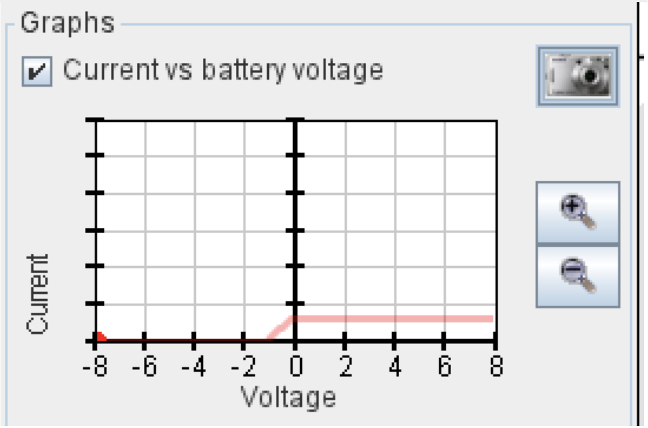
Explanation:

A


Current vs light intensity
Current
Intensity

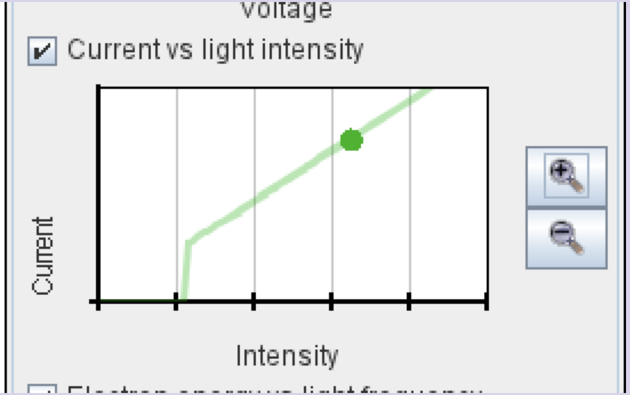

Graphs
Current vs battery voltage
Current
-8 -6 -4 -2 0 2 4 6 8
Voltage


Current vs battery voltage
Current
-8 -6 -4 -2 0 2 4 6 8
Voltage


Graphs
Current vs battery voltage
Current
-8 -6 -4 -2 0 2 4 6 8
Voltage

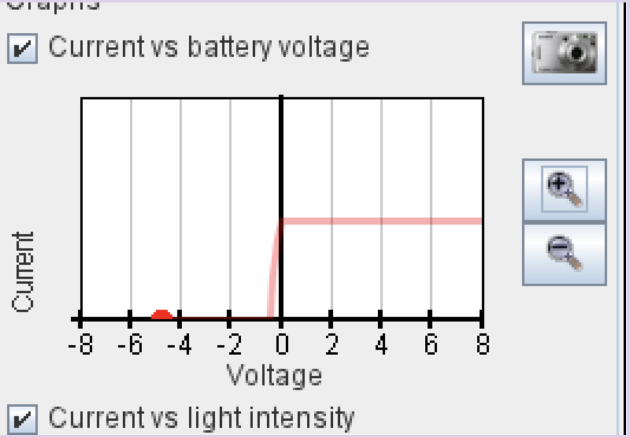
Team 3 ALG 27.2.4 [ALG Chapter 27 Third edition.docx]

Experiment 1: Observed result



Explanation:

Experiment 2: Observed result



Explanation

Team 3 ALG 27.2.4 ALG Chapter 27 Third edition.docx

Experiment 3: Observed result

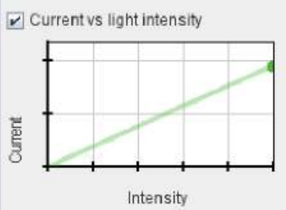
Explanation:

Experiment 4: Observed result

Explanation

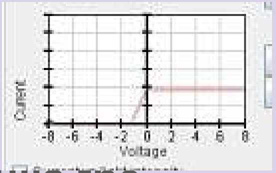
Experiment 5 Explanation

Team 4 ALG 27.2.4 ALG Chapter 27 Third edition.docx



Experiment 1: Observed result

Explanation: **Additional intensity appears to give electrons add’l KE**



Experiment 2: Observed result

Explanation: **With a positive voltage across the battery, the electric field pulls the electrons from the cathode to the anode, creating a current. When the voltage becomes negative, not all of the electrons make it to the anode before being pulled back to the cathode until the negative voltage is so great no electrons leaving the cathode will make it to the anode.**

Team 4 ALG 27.2.4 ALG Chapter 27 Third edition.docx

Experiment 3: Observed result

Explanation: **Similar to exp2, but ⅔ intensity appears to yield ⅔ of the curr**

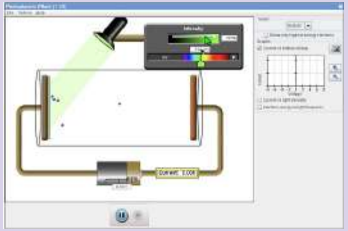
Experiment 4: Observed result

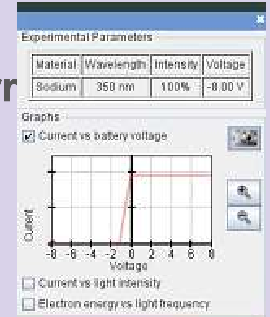
Current observed for wavelengths below 539 nm

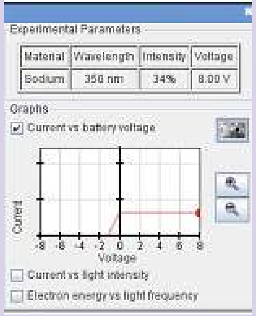
Explanation

Experiment 5 Explanation
Electrons liberated due to the wavelength (color) of

the light and *not* the total energy absorbed
(= intensity x time). Must be a separate interaction
For each electron, not cumulative?







All together ALG 27.2.5

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. Can you explain it using an electromagnetic wave model of light? Elaborate.

Summary

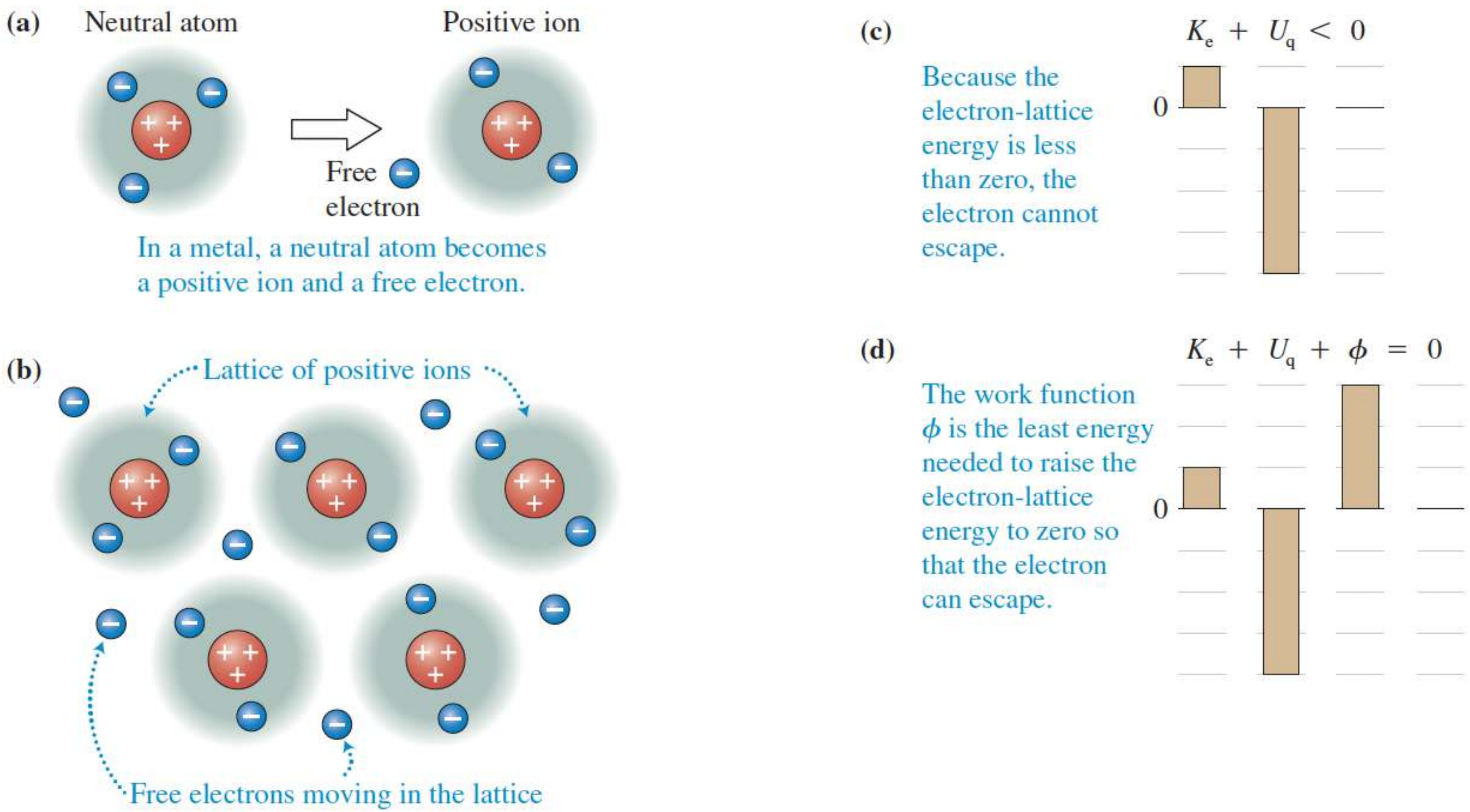
What features of the photoelectric effect the electromagnetic wave model of light cannot explain?

1. The first pattern can be explained.
2.

3.

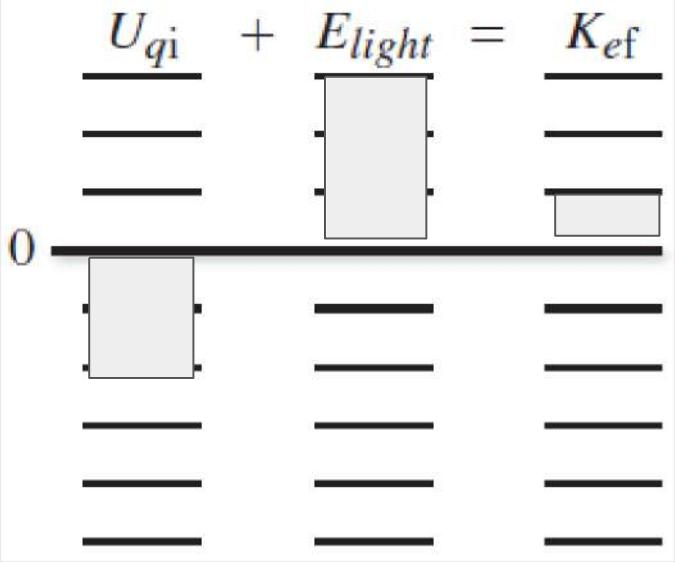
4.

The structure of metals

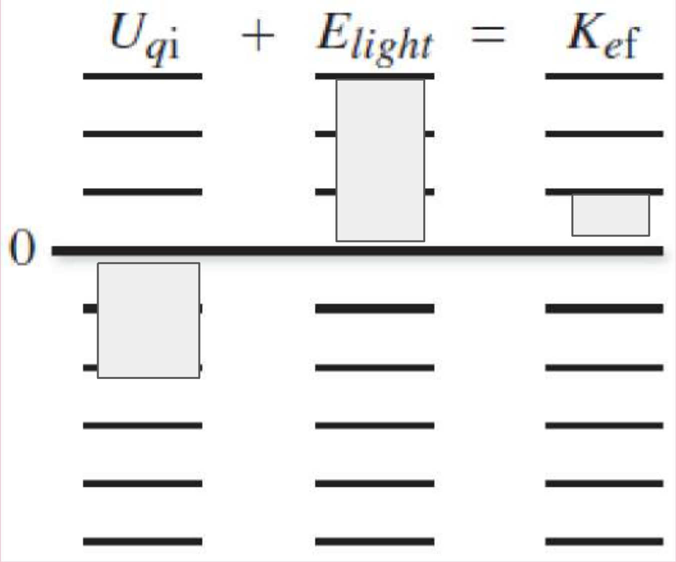


Team 1 ALG 27.3.1 (use the drawing tool to draw bars)

Lenard

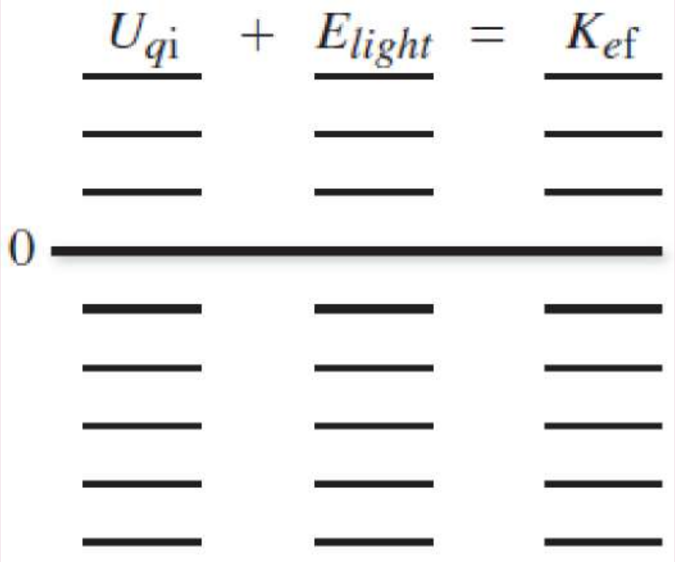


Einstein

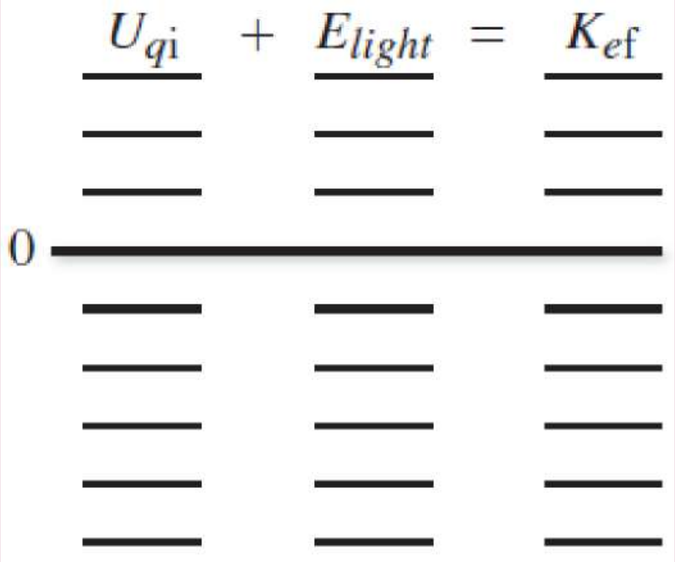


Team 2 ALG 27.3.1 (use the drawing tool to draw bars)

Lenard



Einstein



Team 3 ALG 27.3.1 (use the drawing tool to draw bars)

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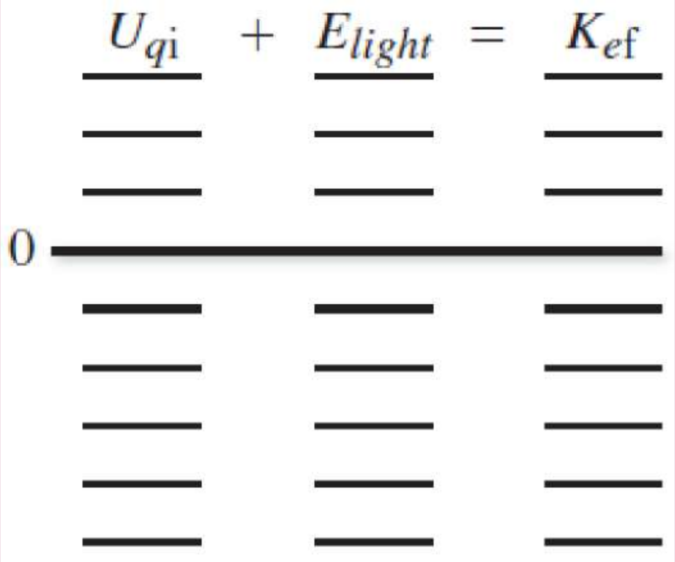

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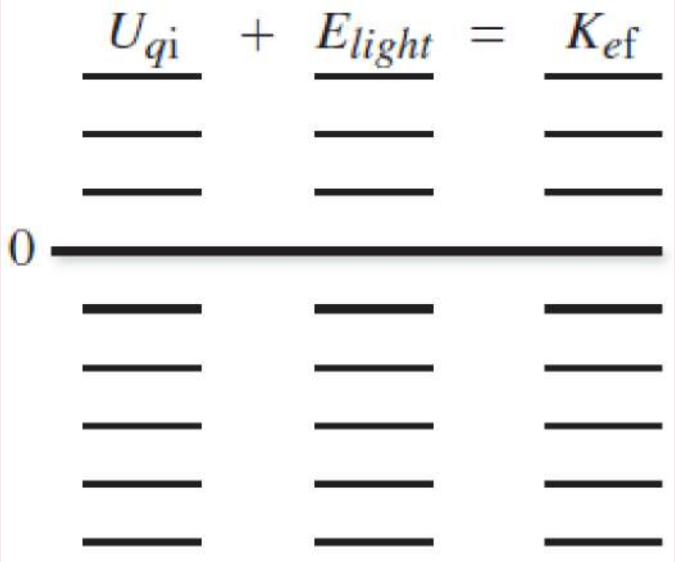
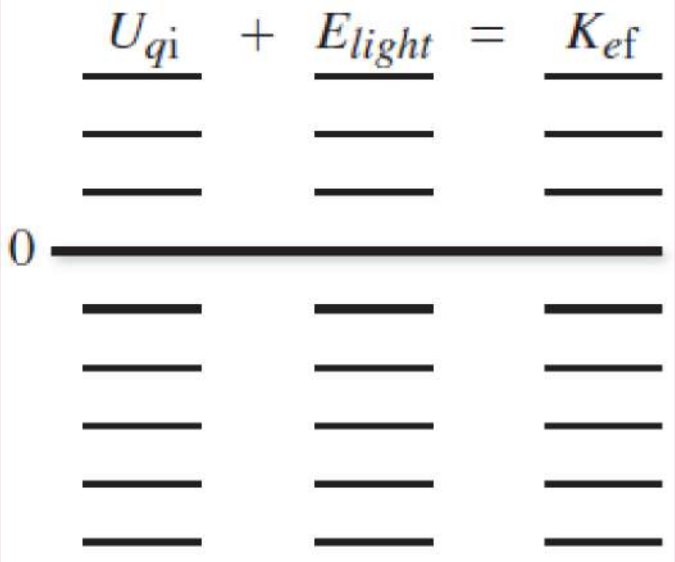
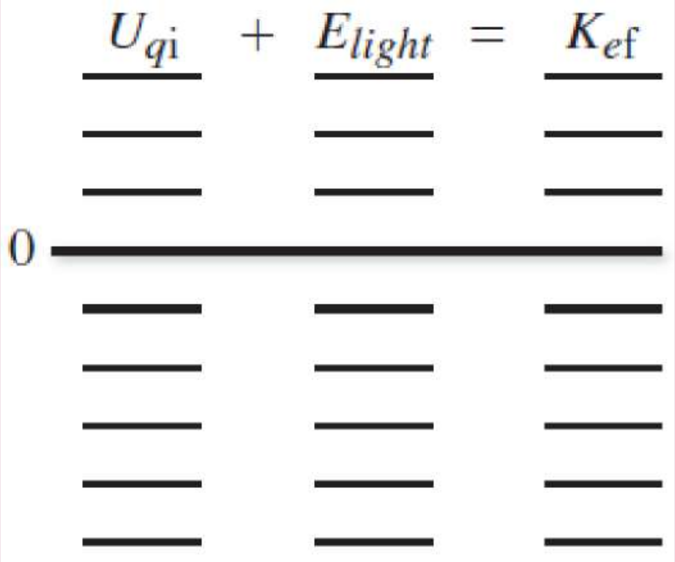


Team 4 ALG 27.3.1 (use the drawing tool to draw bars)

Lenard



Einstein



Einstein's main idea

Objects not only emit light by portions - quanta, but they also absorb light by quanta of light (1905). We call those light quanta (Einstein's term) photons due to Gilbert Newton Lewis (covalent bonds, Lewis pairs in chemistry) who coined the term photon on December 18, 1926, in a letter to the journal Nature.

From Wikipedia: In 1926, he coined the term "photon" for the smallest unit of radiant energy (light). Actually, the outcome of his letter to *Nature* was not what he had intended.[52] In the letter, he proposed a photon being a structural element, not energy. He insisted on the need for a new variable, *the number of photons*. Although his theory differed from the quantum theory of light introduced by Albert Einstein in 1905, his name was adopted for what Einstein had called a **light quantum** (Lichtquant in German).

Einstein's equation for the photoelectric effect During the photoelectric effect, the kinetic energy K_e of the emitted electron equals the difference in the energy of the photon $E_{photon} = hf$ absorbed by the metal and the metal's work function ϕ:

Team 1 ALG 27.3.2 ALG Chapter 27 Third edition.docx

Only explanations for all 5 experiments, no graphs

Experiment 1: Higher light intensity means more photons and so more electrons can be fed and go out the metal.

Experiment 2: (intensity of light fixed, UV light) The current depends on the energy of the photon and the stopping potential.

Experiment 3: intensity here is varied from ⅔ and ⅓, the current is reduced because less photons. The stopping potential ? is the same, is based on the metal we are trying to move the electron of.

Experiment 4: visible light, higher intensity, the energy isn't enough to "overcome" (?) the work function

Experiment 5:

Team 2 ALG 27.3.2 [ALG Chapter 27 Third edition.docx]

Only explanations for all 5 experiments, no graphs

- More intensity more photons, therefore greater current with more electrons ejected.
- The positive voltage doesn't change amount of photons incident on the metal, therefore, doesn't affect current; negative voltage makes some of them not making it to the cathode, and turns them back, therefore reduced the current.
- Exp-4: No matter what intensity is, there is not ejected electrons since electron's gained energy is determined by the single photon's energy
- Exp-5: time is related to kinetic energy of electron which is not related to intensity of light.

Team 3 ALG 27.3.2 ALG Chapter 27 Third edition.docx

Only explanations for all 5 experiments, no graphs

1. Increasing the intensity, increases the number of quanta and consequently the number of electrons.
2. The current depends on the energy of quanta (the frequency).
3. No electrons have enough energy to escape from the metal plate.
4. Just having more quanta of the same energy still doesn't give any electrons enough energy to escape the metal plate.

5.

Team 4 ALG 27.3.2 ALG Chapter 27 Third edition.docx

Pg 27-15. Only explanations for all 5 experiments, no graphs

1. Photocurrent vs. Light intensity (Observed proportional): More “kinetic quanta” of energy liberated more electrons. Perhaps 1 quantum -> 1 photoelectron.
2. Photocurrent vs. Voltage (observed - stopping potential but constant for positive voltage): current measures number of electronics kicked out, not their energies. For negative voltages, electrons need to have enough kinetic energy to climb up the potential difference. But once they can, their excess kinetic energy is not important.
3. Limiting longest wavelength to produce photocurrent: Energy of a light quantum must increase with frequency

Team 1 ALG 27.3.3

H = (phi times lambda)/(c)

1eV = 1.6 times 10^-19 J

Aluminum:

Metal	Work function (eV)	λ_{max} (nm)	Color or type of light
Aluminum	4,06	305	UV
Sodium	2,3	539	green
Cesium	2,1	590	Yellow
Lead	4,14	300	UV
Magnesium	3,66	339	UV
Zinc	4,3	288	UV

Einstein's equation for the photoelectric effect During the photoelectric effect, the kinetic energy K_e of the emitted electron equals the difference in the energy of the photon $E_{photon} = hf$ absorbed by the metal and the metal's work function ϕ:

Team 2 ALG 27.3.3

Metal	Work function (eV)	λ_{max} (nm)	Color or type of light
Aluminum	4,06	305	UV
Sodium	2,3	539	green
Cesium	2,1	590	Yellow
Lead	4,14	300	UV
Magnesium	3,66	339	UV
Zinc	4,3	288	UV

1239
1239, 7
1239
1323
1240
1238,4

Einstein's equation for the photoelectric effect During the photoelectric effect, the kinetic energy K_e of the emitted electron equals the difference in the energy of the photon $E_{photon} = hf$ absorbed by the metal and the metal's work function ϕ:

Team 3 ALG 27.3.3

Metal	Work functio n (eV)	λ_{max} (nm)	Color or type of light
Aluminum	4,06	305	UV
Sodium	2,3	539	green
Cesium	2,1	590	Yellow
Lead	4,14	300	UV
Magnesium	3,66	339	UV
Zinc	4,3	288	UV

Einstein's equation for the photoelectric effect During the photoelectric effect, the kinetic energy K_e of the emitted electron equals the difference in the energy of the photon $E_{photon} = hf$ absorbed by the metal and the metal's work function ϕ:

$$-\phi + hf = K_e \qquad (27.5)$$

Team 4 ALG 27.3.3 - pg 27-16

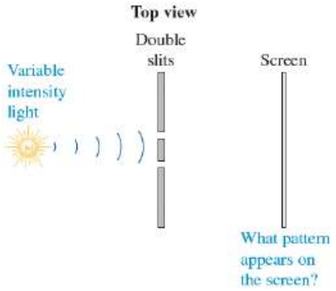
For Millikan's idea, we can calculate Planck’s constant from *h* = phi * c/lambda_max (set electron kinetic energy K = 0 in the equation).
Or we can plot phi vs. 1/lambda_max for these metals and we would see a straight line of slope = *hc*.

Einstein’s equation for the photoelectric effect During the photoelectric effect, the kinetic energy K_e of the emitted electron equals the difference in the energy of the photon $E_{photon} = hf$ absorbed by the metal and the metal’s work function ϕ:

Sergei Vavilov- an unknown name

TESTING EXPERIMENT TABLE 27.7 Do photons have both wave-like and particle-like properties?

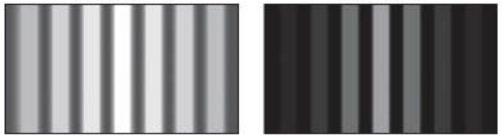
Testing experiment	Prediction	Outcome
Use a light source with variable intensity. Shine the light on two narrow slits. Place a fluorescent screen beyond the slits that indicates where light hits the screen.	**Particle model:** Only two bright bands should appear—images of the slits themselves. As intensity decreases, we expect to see individual flashes caused by single photons at the slit image locations.	The experimental outcome is identical to the dual wave-particle model's prediction.



High intensity Low intensity

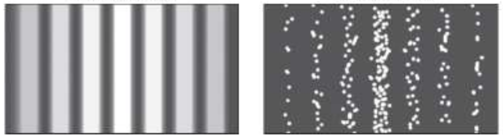
Wave model: Many alternating bright and dark bands should appear. As the intensity decreases, we expect all of the bright bands to become uniformly dimmer until they disappear.

High intensity Low intensity



Dual wave-particle model: Many alternating bright and dark bands should appear. As the intensity decreases, we expect to see individual flashes due to single photons at bright band locations only. At the locations of the dark bands no flashes should be seen.

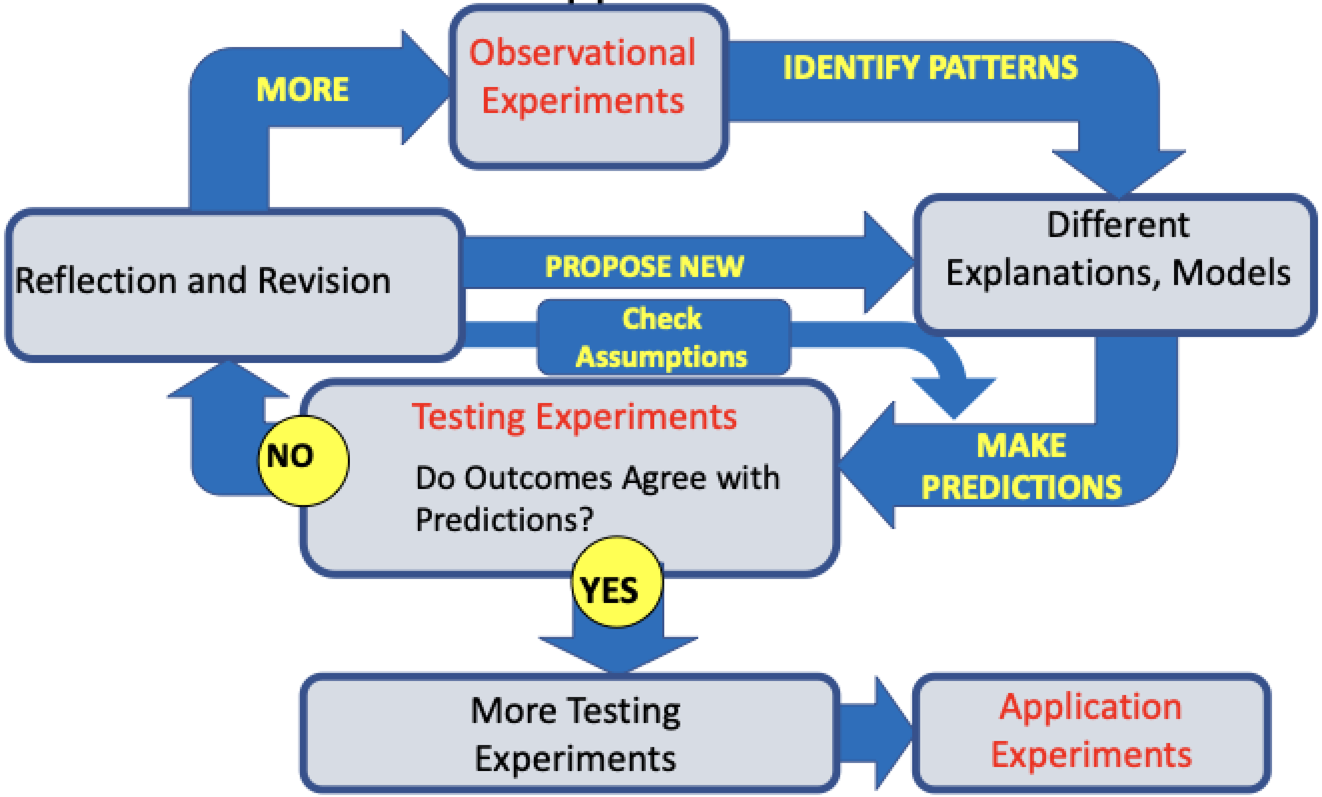
High intensity Low intensity



Conclusion

- Photons hit the screen, indicated by the flashes at low intensity.
- The photons only reach the screen at places where constructive wave interference occurs.
- Photons are simultaneously exhibiting both wave-like and particle-like behaviors.

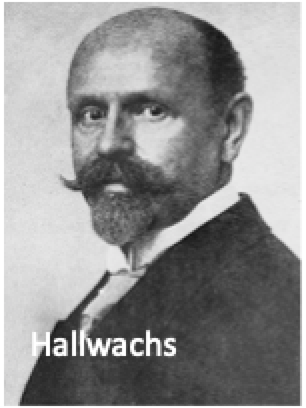
The Investigative Science Learning Environment (ISLE) approach



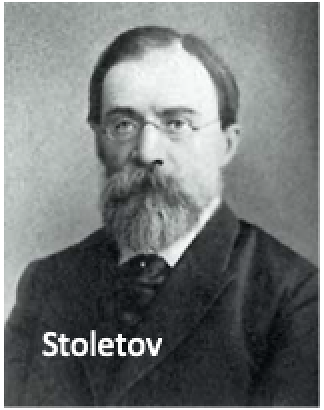
Etkina and Van Heuvelen, 2001, 2007; Etkina, 2015, Etkina et al., 2019

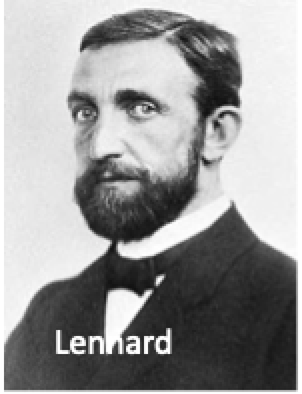
History of science: Photoelectric effect

Accidental
observation



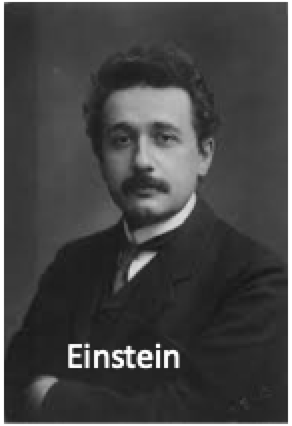
Qualitative observational
experiments



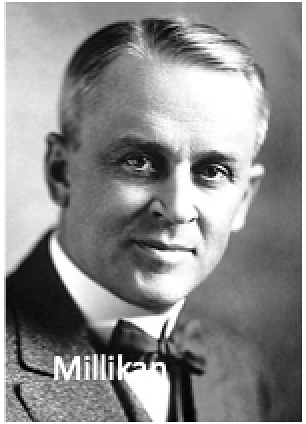


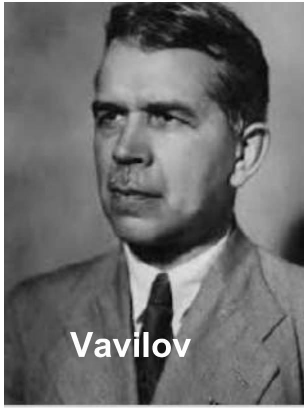
Quantitative observational
experiments and explanations

Assumption



Explanation

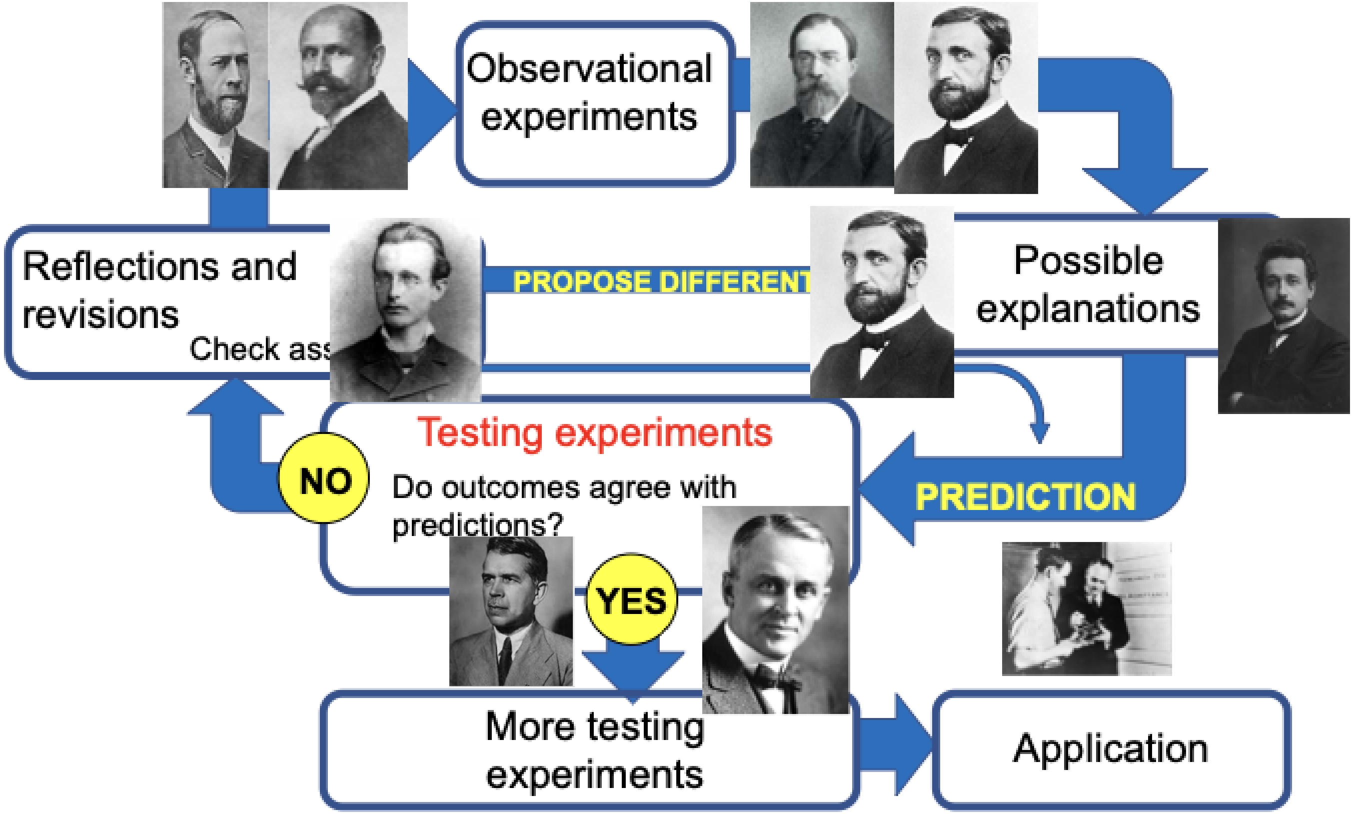




Testing
experiment,
prediction,
outcome

Application (photomultiplier

Investigative Science Learning Environment - ISLE



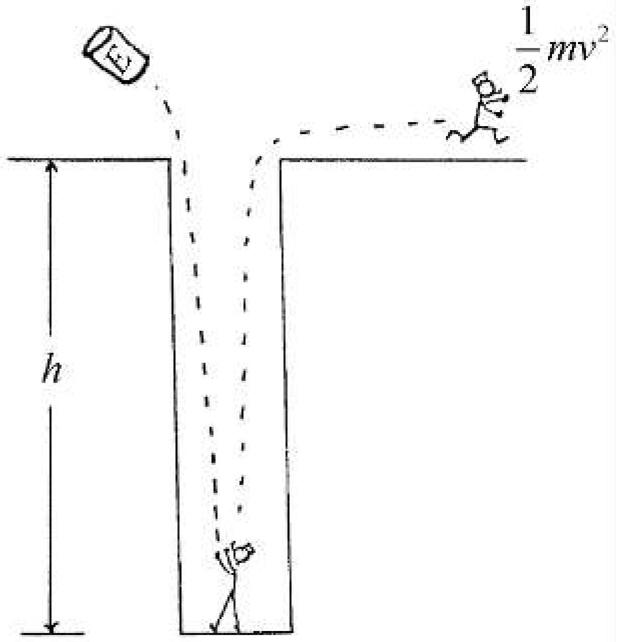
Analogies

In the literature, you can find the following mechanical analogy for the Einstein's equation that describes the energy changes in a photoelectric effect:

A student is trapped in a well with depth *h* (see figure below). A friend throws her a can of energy drink. When the student drinks the drink, she gets enough energy to climb out of the well. The rest of the energy she received from the drink goes for her kinetic energy when she climbs out of the well.

a. Identify and describe the relevant elements and/or relationships (including equations) in the base (analogy) and in the target.

b. Describe the most important limitations of the analogy.



Adapted from: Carl H. Hayn, »Analogy for Einstein's photoelectric equation«, *Phys. Teach*. **20**, 314 (1982)
https://doi.org/10.1119/1.2341044

Team 1

Base	Target
Energy drink	
Energy to lift the student from the well (mgh)	
Student	
Earth	
Student’s kinetic energy	
The well	

b. Describe most important limitations of the analogy.

Team 2

Base	Target
Energy drink	
Energy to lift the student from the well (mgh)	
Student	
Earth	
Student's kinetic energy	
The well	

b. Describe most important limitations of the analogy.

Team 3

Base	Target
Energy drink	
Energy to lift the student from the well (mgh)	
Student	
Earth	
Student’s kinetic energy	
The well	

b. Describe most important limitations of the analogy.

Team 4

Base	Target
Energy drink	
Energy to lift the student from the well (mgh)	
Student	
Earth	
Student’s kinetic energy	
The well	

b. Describe most important limitations of the analogy.

Team 1 27.4.1-27.4.4 ALG Chapter 27 Third edition.docx

Team 2 27.4.1-27.4.4 ALG Chapter 27 Third edition.docx

Team 3 27.4.1-27.4.4 ALG Chapter 27 Third edition.docx

Team 4 27.4.1-27.4.4 ALG Chapter 27 Third edition.docx

Team 1 27.4.6

Team 2 27.4.6

Team 3 27.4.6

Team 4 27.4.6

What did you learn today?

I learned about the specific experiments that led to the understanding of the photoelectric effect.

I learned how challenging it is to readjust my paradigm and remember how the photoelectric effect started out from the wave perspective. Re-visiting that mindset took some effort after years of working with the particle model.

I enjoyed the history and the analogy with Popeye! I was also interested in learning about Soviet contributions. Using the electroscope as an intro to this topic was something I hadn't thought of. Unfortunately, the humidity in Florida makes it very hard to do electrostatic experiments.The logistics of watching the zoom, and the ALG, and Youtube, and my notes, and a breakout group–it was challenging at first, but I got the hang of it!

I already do a lot of potential wells for intro Ug and Ue and upper level Schrodinger, need to make better description for the intermediate students in Modern Lab doing photoelectric effect. Bring single photon experiment into Modern Lab from the Quantum Lab?

The photoelectric effect as topic fits in all the components of the ISLE process.

The historical process of discovery of the photoelectric effect with the sequence of observational and testing experiment is very beautiful

The historical process and the different perspective of teaching the quantum optics.

The use of electroscope with discharging UV light experiment easy to be done in class :)

That I need add'l review of underlying ideas (e.g., electroscope use, induction, ...)

What did you learn today?

How to control the conversation into small chunks in order to move onto the next idea. And letting students come to their own conclusions. What I'm looking for is more examples of "unknown" physicist who really did all of this simultaneously or even before those who came before them.