Exam 3 Information

- Exam Date: Wednesday Apr. 17, 6 -7:25 pm.
- Conflict Exam, Thursday Apr. 18, 6 – 7:25 pm.
  - Available to students with legitimate time conflict with regularly scheduled exam.
  - You must submit a request to your section professor and Prof. Ciolek by email <u>by 5 pm Monday, Apr. 15</u> that you would like to take the conflict exam and state the reason why.
  - We reserve the right to deny a student from taking the conflict exam if it is determined that there is not a legitimate reason for taking the exam at that alternate time, or if they have not submitted a request from instructors in advance, as required above.
- Students with accommodations
  - Remind your section instructor of your exam accommodations.
  - Exam will be taken in 2C14 of the J-Rowl Science Center. Bring a copy of your official notice of accommodations to the exam room.
  - Start at the regular time and submit at the agreed time.

Exam 3 Information (2)

- Allowed resources –
  - You may use you a calculator with capabilities and functions up to the TI-Nspire. Devices with communication/internet capability are not allowed.
  - You are allowed a single $8.5'' \times 11''$ sheet of paper (both sides) crib sheet. Must be a single piece of paper – no taped or stapled pages.
  - Writing instruments (pencils, pens). For pens, darker inks are preferred. Red ink is <u>not</u> allowed.
- A short table of physical constants (same as done for Exams 1 & 2) will be included on the first page of the Exam 3 test booklet.

Exam 3 Information (3)

- Exam will focus on topics presented in classes 17, 18, and 20-24.
- Exam Structure
  - Multiple choice and numerical short answer questions for ~ 70% to 80% of exam pts.
    - ✓ ~ ½ conceptual and scaling questions
    - ✓ ~ ½ numerical solution
  - Free response questions for the remaining % of exam pts.
- Good resources
  - MasteringPhysics: Lecture quizzes; Practice Problems; Homework
  - Exam Archives (LMS)
  - Activity worksheets
  - Lecture slides
  - Text
- Monitor your email and LMS announcements for exam information and updates.

Exam 3 Information (4)

Class Section	Instructor	Exam Room
1, 2	Robles Sanchez	West Hall Auditorium
3, 4	Zheng	Amos Eaton 214
5	Persans	Sage 3303
6,7	Schroeder/Ciolek	West Hall Auditorium
8, 9	Martin	Sage 3303
Accommodations	All	2C14 J-Rowl SC

Physics 1200
Lecture 24
Spring 2024

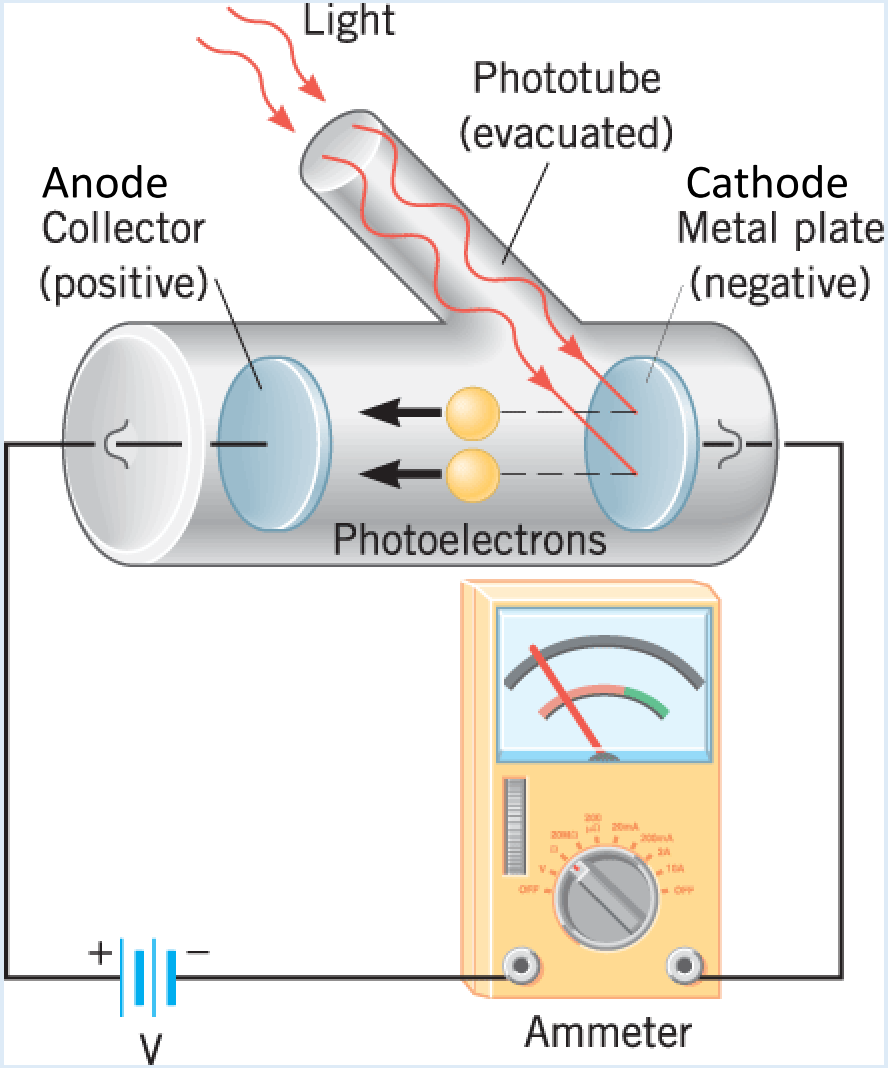
Photons, Photon Energy – Photoelectric Effect,
Photon Momentum – Compton Effect

Einstein & The Photoelectric Effect

- In 1921 Einstein was awarded the Nobel Prize in Physics. In the citation for his prize, it was stated that he was receiving the award based on his "services in theoretical physics, and especially for his discovery of the law of the photoelectric effect".
  - There was no explicit mention of the theory of relativity – special or general – by the committee that awarded him the prize. A lot of people even then still had problems accepting relativity.
  - Einstein presented his theory for the explanation of the photoelectric effect in 1905, the same year he put forth the theory of relativity (including the mass-energy relation), and a landmark paper on his theory of Brownian motion (i.e., the random, jittery motion of very small objects in a fluid). 1905 was an incredibly productive year for Einstein (and for Physics). 1905 sometimes referred to as Einstein's "Annus Mirabilis" (Miracle Year).

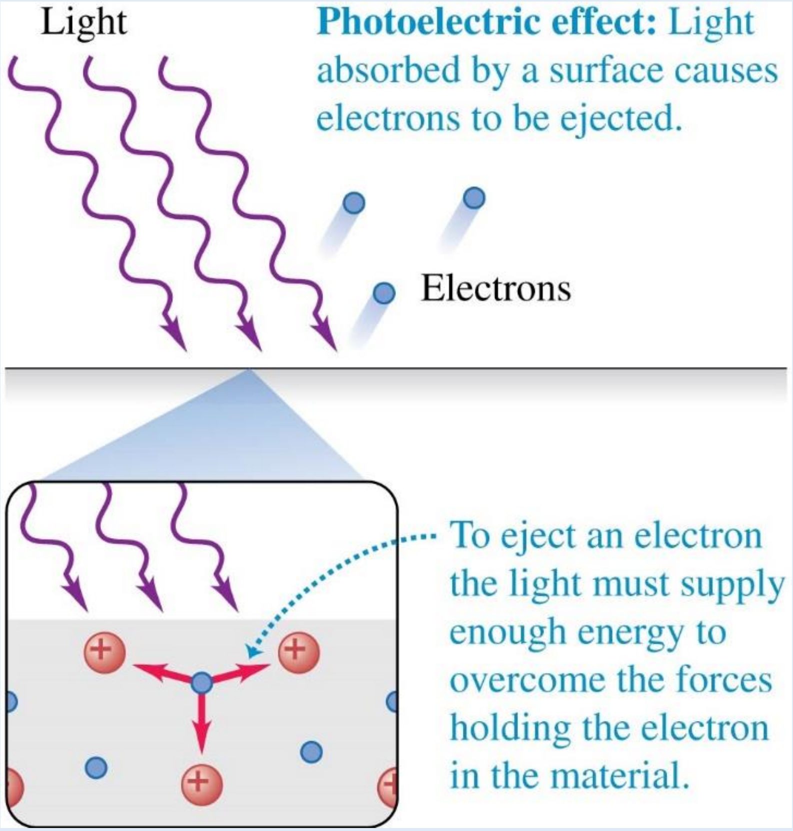
The Photoelectric Effect Experiment

- Earliest experiments investigating this by H. Hertz (1887, who also experimentally verified Maxwell's prediction of emission of electromagnetic waves by accelerated charges), and by P. Lenard (1900).



The Photoelectric Effect Experiment-Analysis

- To escape from a surface, an electron must absorb enough energy from the incident light to overcome the attraction of positive ions in the material.
- Attractions constitute a potential-energy barrier; the light supplies the “kick” that enables the electron to escape.
- Ejected electrons form what is called a <u>photocurrent</u>.



The Photoelectric Effect Experiment-Analysis (2)

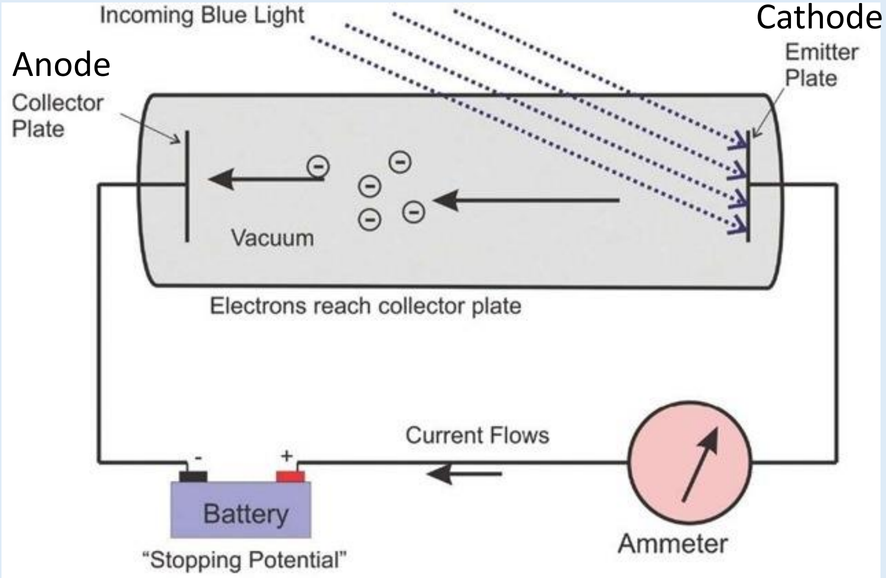
- Electrons are ejected from the illuminated emitter plate (cathode) & travel to the collector plate (anode).

- Energy of freed electrons is conserved. For electrons travelling from cathode (C) to anode (A), conservation of energy gives:

$$K_{\mathrm{C}} - eV_{\mathrm{C}} = K_{\mathrm{A}} - eV_{\mathrm{A}}$$

$$\Rightarrow K_{\mathrm{A}} = K_{\mathrm{C}} + e(V_{\mathrm{A}} - V_{\mathrm{C}}) = K_{\mathrm{C}} + eV_{\mathrm{AC}},$$

K is the kinetic energy, V is the electric potential at A or C, and $V_{AC} \equiv V_A - V_C$.



- When battery polarity is reversed (shown in figure), the potential between the plates slows down electrons approaching anode. The <u>stopping potential</u> $V_0 = -V_{\mathrm{AC}}$ is the potential that just stops the current from getting to the anode, that is, the potential that causes $K_{\mathrm{A}} = 0$.

    - The maximum kinetic energy of the ejected cathode electrons for that case is

$$K_{\mathrm{C,max}} + eV_{AC} = 0 \quad \Rightarrow \quad K_{\mathrm{C,max}} = -eV_{\mathrm{AC}} = eV_0 \quad \Rightarrow \quad \boxed{K_{\mathrm{C,max}} = eV_0}\ .$$

The Photoelectric Effect Experiment – Key Results

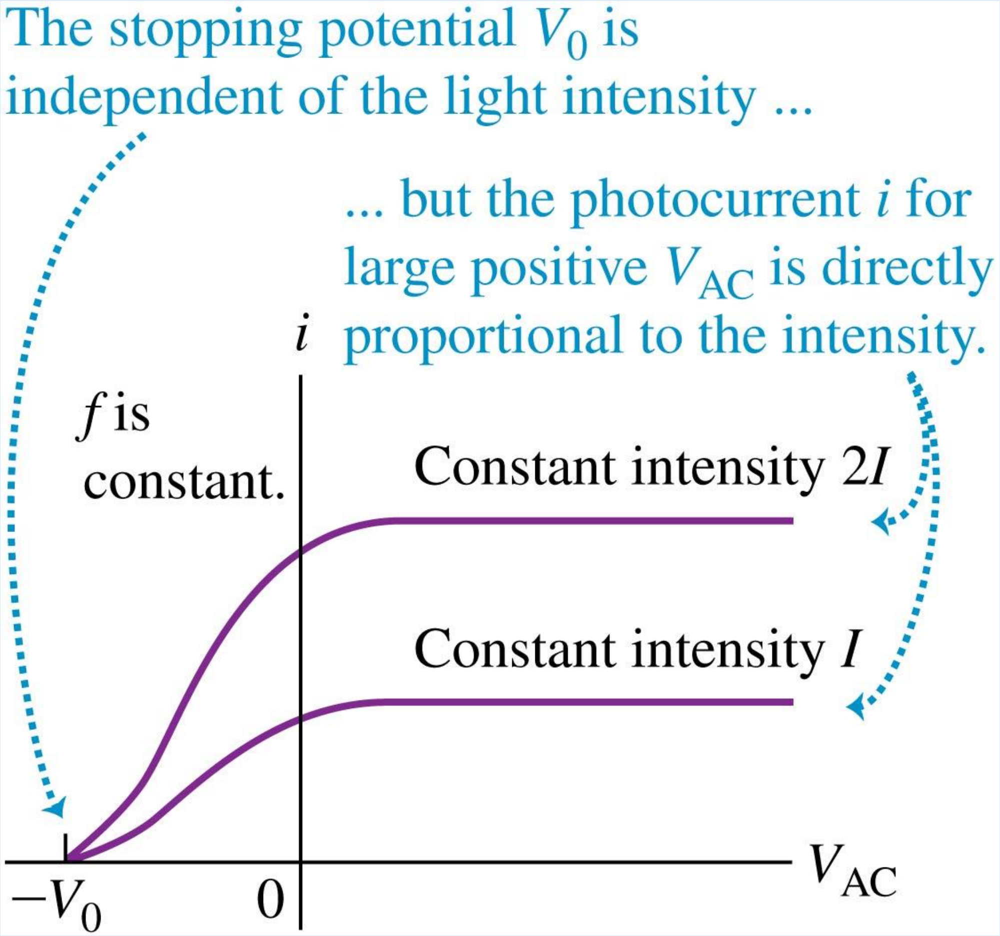
1. Photocurrent depends on light frequency. For a given material, monochromatic light with a frequency below a minimum threshold frequency produces no photocurrent, regardless of intensity. (Contrary to EM wave prediction: intensity of light is proportional to the square of the electric field amplitude, independent of frequency.)

2. No measurable time delay between when light is turned on and when cathode emits photoelectrons (when the light frequency exceeds the threshold). Found true no matter how faint the light is. (Contrary to EM wave prediction: energy absorbed by an electron is the time integral of absorbed power. Should be a time delay for absorption of sufficient energy to eject an electron from the metal.)

3. Stopping potential does not depend on intensity but does depend on frequency. Only effect of increasing intensity is to increase the number of electrons per second, and hence, the photocurrent i. The greater the light frequency, the greater the energy of the ejected photoelectrons. (Contrary to EM wave model prediction: intensity of EM wave is proportional to electric field amplitude, and the electric field does work on the electron in the metal that causes it to be ejected. Hence, higher intensity should result in electrons with greater kinetic energy when ejected – thus requires greater stopping potential to halt current.)

Photocurrent in Photoelectric Effect Experiments

- Graphs show photocurrent as a function of potential difference V_{AC} for light of a given frequency and two different intensities.
- The reverse potential difference $-V_0$ needed to reduce the current to zero is the same for both intensities.



Einstein’s Proposal: Photons

- To explain the photoelectric effect, Einstein made the radical postulate that a beam of light consists of small, discreet packages of energy called <u>photons</u>, or quanta. (“Quanta” is the plural form of “quantum”.) He also postulated:
  - Photons in vacuum travel at the speed of light in vacuum, c. They have <u>zero mass</u>.
  - The energy of an individual photon is:

$$\boxed{E = hf = \frac{hc}{\lambda}},$$

f and λ are the frequency and wavelength of the photon (same as for the electromagnetic wave associated with the photon) , and h is <u>Planck’s constant</u> ($h = 6.626 \times 10^{-34}\ \mathrm{J \cdot s}$, in SI units), also known as the “quantum of action”.

- The fundamental physical constant h was first proposed and calculated by Max Planck (1900) to solve the inability of classical electromagnetic wave theory to explain “cavity radiation” (radiation in thermal equilibrium with matter in a cavity, also called “blackbody radiation”).
  - Planck’s cavity radiation solution was the first major step toward the theory of quantum mechanics. He won the Nobel Prize in Physics for this work in 1918.
  - Einstein’s photon hypothesis was a dramatic extension of Planck’s idea. It was the second major step on the road toward quantum mechanics.

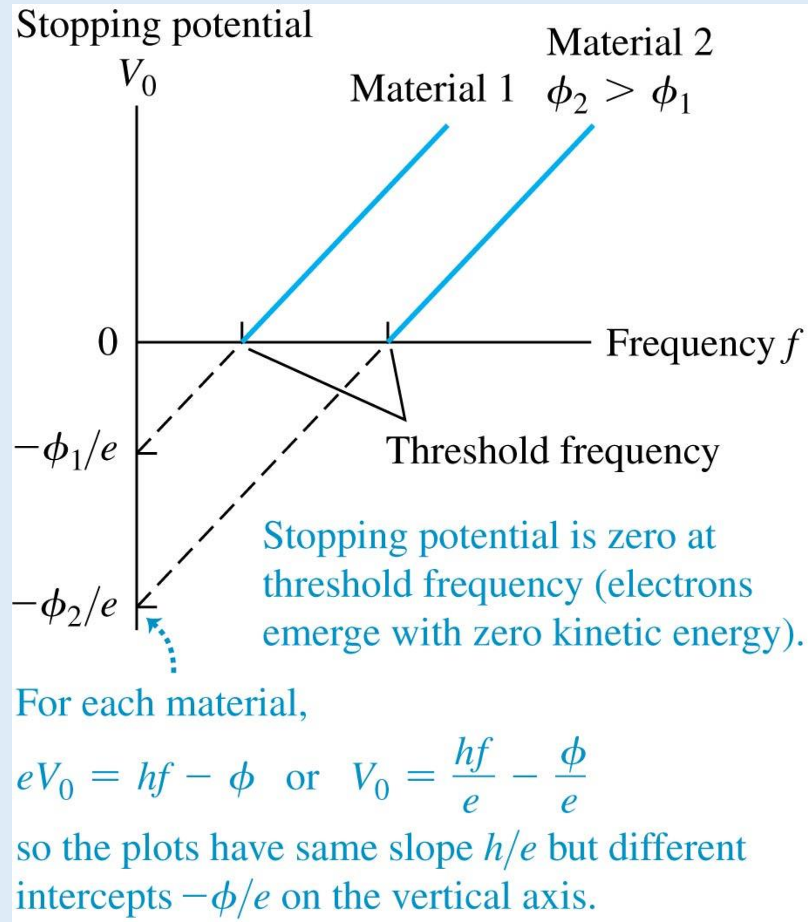
Einstein's Proposal: Photons (2)

- Individual photon arriving at a surface is absorbed by a single electron.
- Einstein proposed the maximum kinetic energy of ejected photoelectrons from a surface is

$$\boxed{K_{\mathrm{C,max}} = eV_0 = hf - \phi},$$

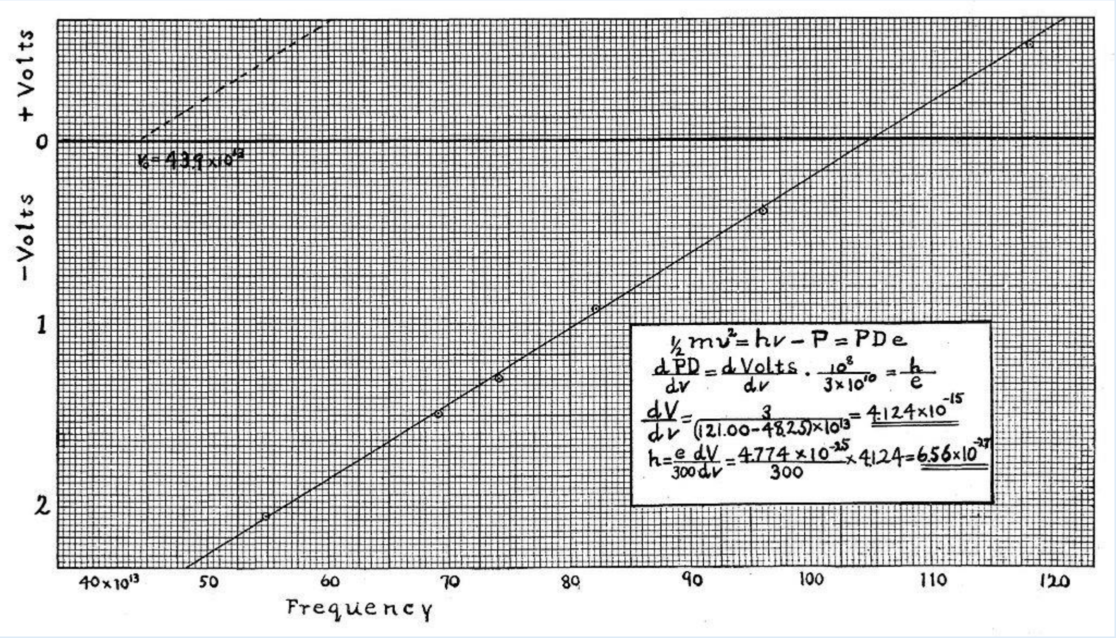
ϕ is the work function of a metal, which is an indication of the energy needed to eject electrons from the bulk metal.

- Electron can escape from the surface ($K_{\mathrm{C,max}} > 0$) only if the energy it absorbs is greater than the work function ϕ.
  - ➢ Explains how energy of emitted electrons in the photoelectric effect depends on light frequency: the greater the work function of a material, the greater the minimum frequency needed to emit photoelectrons. Thus, there is a threshold frequency.



Einstein's Photon Proposal: Verified by Millikan

- R. A. Millikan performed photoelectric experiments attempting to disprove (!!!) Einstein's photon hypothesis.
- He performed the experiment sketched in the figure on the preceding slide (which is also be doing in your lab today). Shown is a hand-drawn graph of his experimental data.



- He found that his data could be used to calculate h, as predicted by Einstein.
- He was very disappointed in his experimental result: he thought that it couldn't be correct, because it contradicted the electromagnetic wave theory of light.
- He was awarded the Nobel Prize in Physics in 1923, partly for his photoelectric effect experiment, and for his experiment that was the first to calculate the charge of an electron (the 'oil-drop experiment').

Work Functions

Element	Work Function (eV)
Aluminum	4.3
Carbon	5.0
Copper	4.7
Gold	5.1
Nickel	5.1
Silicon	4.8
Silver	4.3
Sodium	2.7

EM Wave Intensity in the Photon Description

- When discussing EM waves, we introduced wave intensity:

$$\text{Intensity } I = \frac{Power}{Area} = \frac{(EM\ Wave\ Energy)}{(Time)(Area)}\ .$$

- For photons, this could be written using the following considerations:
  - ➢ The energy of a single photon is $\boxed{E_\gamma = hf}$.
    (Because photons are relativistic particles, γ is often used as the symbol to denote a photon.)
  - ➢ If there are N_γ photons in the EM wave, all having the same frequency f, the total EM wave energy $= N_\gamma\ hf$.
  - ➢ Follows that, when using the photon description, the intensity is

$$\boxed{I = \frac{N_\gamma hf}{(Time)(Area)} = \left[\frac{N_\gamma}{(Time)(Area)}\right] hf = F_\gamma E_\gamma}\ , \text{ where}$$

$$\boxed{F_\gamma = \frac{(N_\gamma)}{(time)(Area)} = \text{photon flux.}}$$

Concept Question

A photoelectric cell is illuminated by light of wavelength λ and a photocurrent i is observed under forward bias. One way to double the current is to

A. Halve the wavelength λ .

B. Halve the photon flux.

C. Double the voltage bias.

D. Double the wavelength λ.

E. Double the photon flux.

Concept Question Solution

The photocurrent is given by the relation

$i = e\frac{dN_e}{dt}$, where $\frac{dN_e}{dt}$ = number of emitted photoelectrons/sec.

For every emitted photoelectron, one photon was absorbed.

$\Rightarrow \frac{dN_e}{dt} = \frac{dN_\gamma}{dt}$ = rate at which photons are incident on the photoelectric cell.

For a photocell with a fixed area,

$\frac{dN_\gamma}{dt} = F_\gamma A_{cell}$, where A_{cell} = surface area of photocell, and

F_γ = incident photon flux.

$\therefore i \propto \frac{dN_\gamma}{dt} \propto F_\gamma$

$\Rightarrow$ To double i , must double F_γ.

Answer: Double the photon flux (E).

Photon Momentum

- Last class we derived the relativistic energy-momentum relation:

$$E^2 = (pc)^2 + (mc^2)^2 \ .$$

  Relation shows that every object having energy also has momentum.

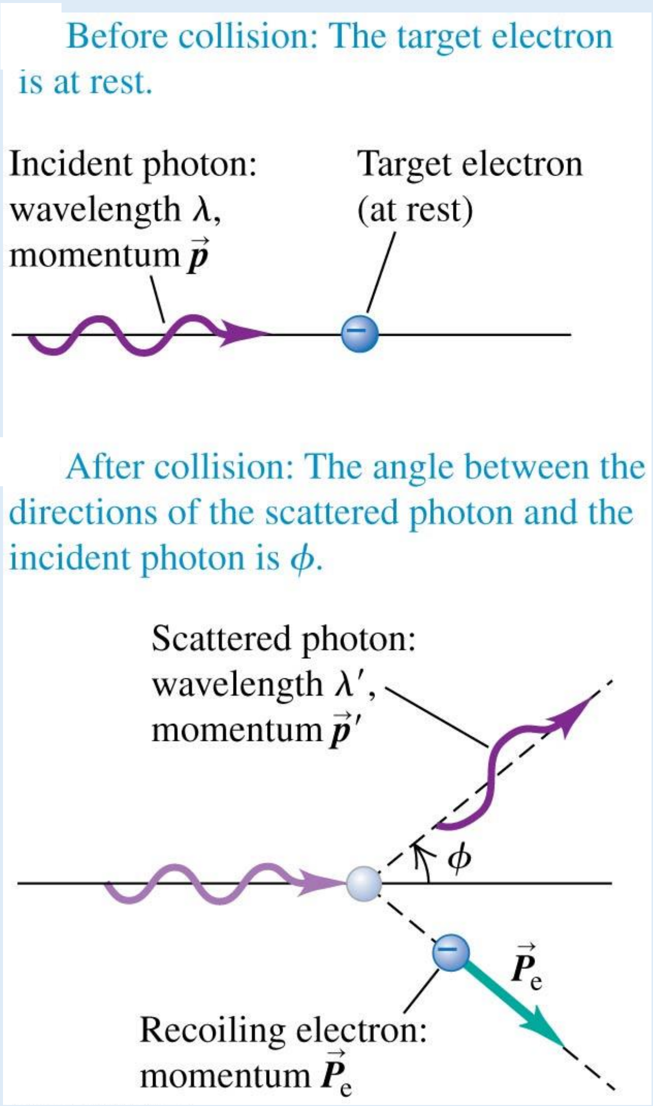
- Because they travel at the speed of light, photon mass $m = 0$.
- Follows that, for photons, $E^2 = (pc)^2$

$$\Rightarrow \boxed{p = \frac{E}{c} = \frac{hf}{c} = \frac{h}{\lambda}}$$ = magnitude of photon momentum.

- The direction of the photon's momentum is in the same direction as the energy transport, which is the same as the direction that the wave propagates (travels).

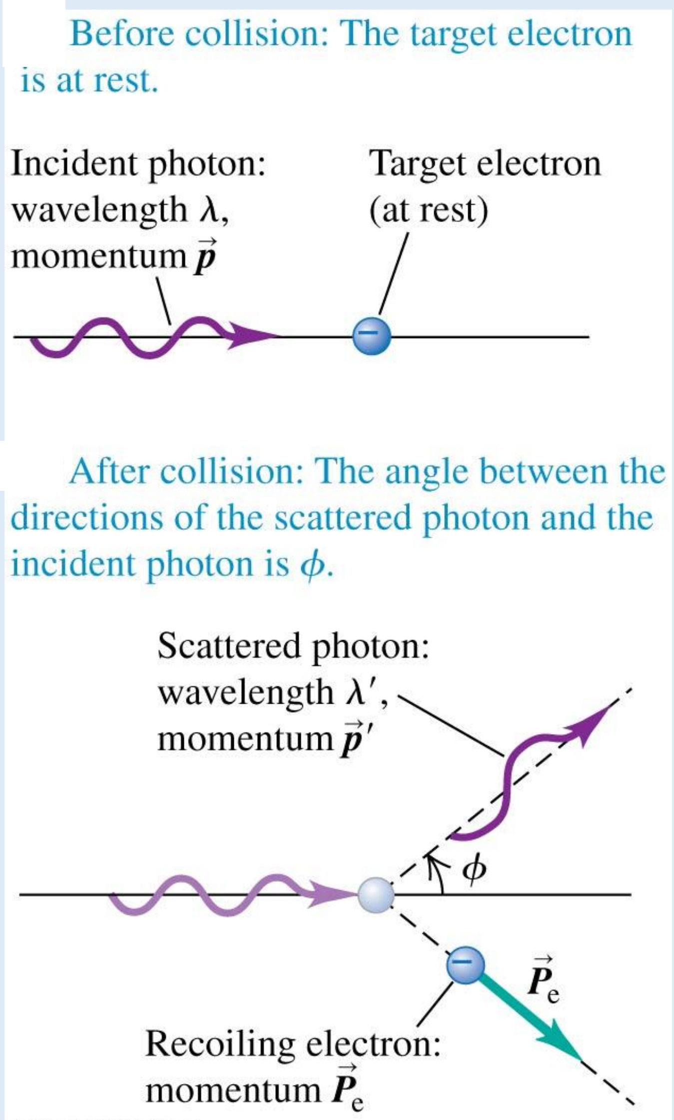
Photon Momentum – The Compton Experiment

- In a 1922 experiment, A. Compton was able to demonstrate for the first time the particle-like effect of the momentum of an X ray photon in an electron-photon collision. The process is now known as the "Compton effect," or "Compton scattering."
  - He was awarded the 1927 Nobel Prize in Physics because of that experiment.
- In the Compton experiment, X rays are scattered from electrons.
  - Scattered X rays have longer wavelengths than incident X rays, and their scattered wavelength depends on scattering angle ϕ.



Photon Momentum – The Compton Experiment (2)

- In <u>Compton scattering</u>, an incident photon collides with an electron that is initially at rest.
  - ➢ The photon gives up part of its energy and momentum to the electron, which recoils as a result of this impact.
  - ➢ Scattered photon flies off at an angle ϕ with respect to the incident direction, but it has less energy and less momentum than the incident photon.
  - ➢ $\therefore$ The wavelength of the scattered photon λ' is longer (greater) than the wavelength λ of the incident photon.



Photon Momentum – The Compton Experiment (3)

- Using conservation of total momentum-energy of the X ray and electron system, the change in the wavelength of the scattered photon is

$$\boxed{\lambda' - \lambda = \frac{h}{mc}(1 - \cos\phi)} \,,$$

where $\lambda =$ wavelength of the X ray photon before collision,

$\lambda' =$ wavelength of the photon after collision,

$\phi =$ angle photon has been scattered with respect to its initial direction of propagation,

$m =$ electron mass,

$c =$ speed of light, and

$h =$ Planck's constant.

- Note: $\frac{h}{mc} = 2.426 \times 10^{-12}$ m. This quantity is referred to as the "Compton wavelength".

Photon Properties: Summary

Photons are electromagnetic wave (light) quanta. Have the following characteristic properties.

- Energy: $E = hf = hc/\lambda$.
- Momentum magnitude: $p = h/\lambda$.
- Wavelength: $\lambda = hc/E$.
- Frequency: $f = E/h$.
- Mass: $m = 0$.
- Propagation speed: $v = c$.

Terms You Should Know

- Photon – a quantum of electromagnetic radiation
- Photon Flux – the number of photons passing through a unit area per unit time (units: $\mathrm{m}^{-2}\ \mathrm{s}^{-1}$).
- Photoelectric effect – ejection of an electron from a material when photons of sufficient energy strike the surface
- Work function – the minimum amount of energy a photon must have to eject an electron from a given material.
- Planck's constant – the ratio of the energy of a photon to its characteristic frequency.
- Compton scattering – scattering of a photon from an electron, conserving momentum and energy.

Light: Waves or Particles?

- Physical experiments reveal that light has a <u>dual</u> nature: a "wave-particle duality."
- No single model or interpretation (EM wave model, photon particle-like model) suffices in describing <u>all</u> physically observed aspects of light (propagation, interaction with matter, etc.).
- It comes down to: what sort of experiment is being performed?
  - ➢ If an experiment is designed to observe the wave-like properties of light, the wave-like properties of light (e.g., two-slit interference, diffraction etc.) are in fact observed.
  - ➢ If an experiment is designed to observe the particle-like properties of light, the particle-like aspects of light (e.g., photoelectric effect, Compton scattering, etc.) are in fact observed.

Discussion Question 1

Light in beam A has a wavelength that is twice that in beam B. The energy of a photon in beam A is

A. Twice that in beam B.

B. Half that in beam B.

C. The same as that in beam B.

D. Depends on intensity.

Discussion Question 1 Solution

Photon energy:

$$E_\gamma = hf = \frac{hc}{\lambda} \ .$$

$$\Rightarrow \quad E_{\gamma_A} = \frac{hc}{\lambda_A}, \quad E_{\gamma_B} = \frac{hc}{\lambda_B}.$$

For $\lambda_A = 2\lambda_B$,

$$\frac{E_{\gamma_A}}{E_{\gamma_B}} = \frac{hc/\lambda_A}{hc/\lambda_B} = \frac{\lambda_B}{\lambda_A} = \frac{\lambda_B}{2\lambda_B} = \frac{1}{2}$$

$$\Rightarrow E_{\gamma_A} = \frac{E_{\gamma_B}}{2} \ .$$

Answer: The energy of a photon in beam A is half that of a photon in beam B (A).

Discussion Question 2

The energy in eV of a photon in a red beam of light of wavelength 620 nm is closest to:

A. 0.020 eV.

B. 2.0 eV.

C. 200 eV.

D. $2.0 \times 10^4 \text{ eV}$.

Discussion Question 2 Solution

$$E_\gamma = hf = \frac{hc}{\lambda} = \frac{\left(6.63\times10^{-34}\ \mathrm{J{\cdot}s}\right)\left(3\times10^{8}\ \frac{\mathrm{m}}{\mathrm{s}}\right)}{\left(620\times10^{-9}\ \mathrm{m}\right)}\left(\frac{1\ \mathrm{eV}}{1.6\times10^{-19}\ \mathrm{J}}\right) = 2.01\ \mathrm{eV}.$$

Discussion Question 3

A beam of light with wavelength λ and intensity I_0 has a photon flux F_0. If the wavelength is halved, but the intensity remains the same, what is the new flux?

A. $\frac{F_0}{4}$.

B. $\frac{F_0}{2}$.

C. F_0 .

D. $2F_0$.

Discussion Question 3 Solution

Beam intensity:

$I = E_\gamma F_\gamma = \frac{hc}{\lambda}\ F_\gamma$. (Light of single wavelength: "monochromatic.")

$I_0 = \frac{hc}{\lambda_0}\ F_{\gamma_0}$.

$\frac{I}{I_0} = \frac{\left(\frac{hc}{\lambda}\right) F_\gamma}{\left(\frac{hc}{\lambda_0}\right) F_{\gamma_0}} = \left(\frac{\lambda_0}{\lambda}\right) \frac{F_\gamma}{F_{\gamma_0}} \qquad \Rightarrow\ F_\gamma = \left(\frac{\lambda}{\lambda_0}\right)\left(\frac{I}{I_0}\right) F_{\gamma_0}$

For constant I, $\ I = I_0$.

And, for $\lambda = \frac{\lambda_0}{2}$ (doubles the energy of a photon),

$\Rightarrow \quad F_\gamma = \frac{F_{\gamma_0}}{2}$. $\therefore$ Photon flux is halved.

Answer: $F = \frac{F_0}{2}$ (B).

Lecture Problem 1

When ultraviolet light with a wavelength of 400 nm falls on a certain metal surface, the maximum kinetic energy of the emitted photoelectrons is 1.10 eV.

What is the kinetic energy if the wavelength is changed to 350 nm?

Lecture Problem 1 Solution

Einstein photoelectric law:

$$K_{\max} = hf - \phi = \frac{hc}{\lambda} - \phi \; .$$

$$K_{\max 0} = \frac{hc}{\lambda_0} - \phi \qquad \Rightarrow \phi = \frac{hc}{\lambda_0} - K_{\max 0}$$

$$\Rightarrow K_{\max} = \frac{hc}{\lambda} - \left(\frac{hc}{\lambda_0} - K_{\max 0}\right) = \frac{hc}{\lambda} - \frac{hc}{\lambda_0} + K_{\max 0}$$

$$\Rightarrow K_{\max} = \frac{hc}{\lambda}\left(1 - \frac{\lambda}{\lambda_0}\right) + K_{\max 0} \; .$$

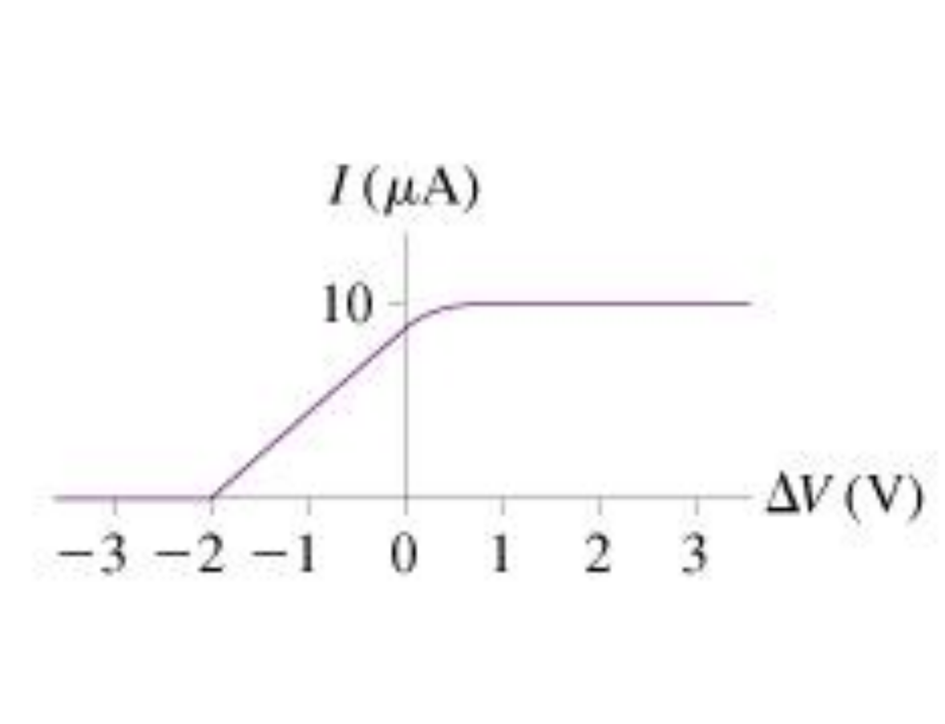
$\therefore$ For $\lambda_0 = 450\ \mathrm{nm}$, $K_{\max 0} = 1.10\ \mathrm{eV}$,

$$K_{\max} = \frac{(6.63 \times 10^{-34}\ \mathrm{J \cdot s})\left(3 \times 10^{8}\ \frac{\mathrm{m}}{\mathrm{s}}\right)}{350 \times 10^{-9}\ \mathrm{m}}\left(1 - \left[\frac{350 \times 10^{-9}\ \mathrm{m}}{400 \times 10^{-9}\ m}\right]\right)\left(\frac{1\ \mathrm{eV}}{1.6 \times 10^{-19} J}\right) + 1.10\ \mathrm{eV}$$

$\Rightarrow K_{\max} = 1.54\ \mathrm{eV}$.

Lecture Problem 2

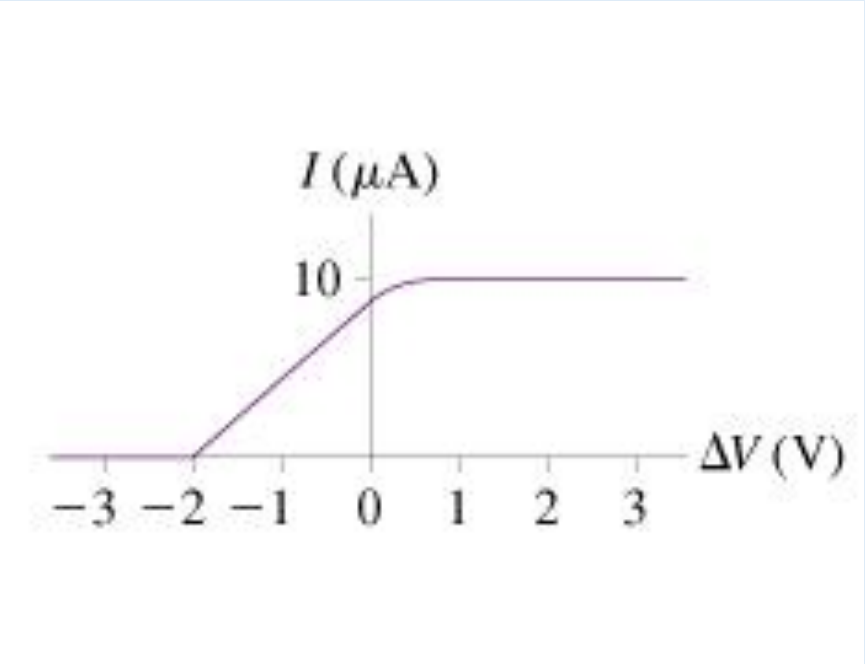
How many photoelectrons are ejected per second in the experiment represented by the graph?



Lecture Problem 2 Solution

$$I = e\frac{dN_e}{dt}$$

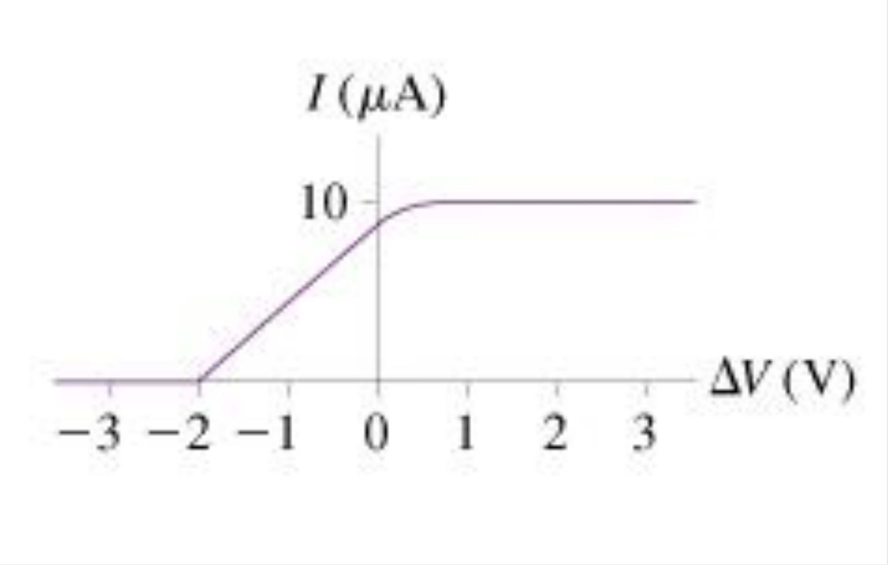
$$\frac{dN_e}{dt} = \frac{I}{e} = \frac{10\times10^{-6}\text{A}}{1.60\times10^{-19}\text{C}} = 6.25\times10^{13}\ \text{s}^{-1}.$$



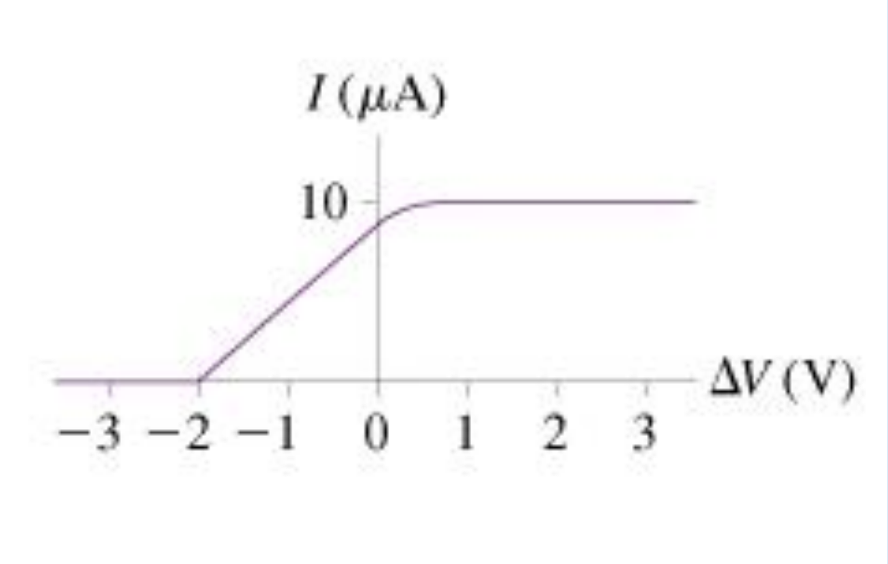
Lecture Problem 3

The wavelength for the experiment shown was 413 nm.

How many photoelectrons per second would be emitted if the wavelength were 2480 nm?



Lecture Problem 3 Solution



From graph, stopping potential:

$V_0 = 2.0 \text{ V}.$

Einstein relation:

$K_{\max} = eV_0 = \frac{hc}{\lambda} - \phi$

For $\lambda_0 = 413 \text{ nm},$

$\phi = \frac{hc}{\lambda} - eV_0$ = work function of metal

$$\phi = \frac{(6.63\times10^{-34}\ \mathrm{J{\cdot}s})(3\times10^{8}\frac{\mathrm{m}}{\mathrm{s}})}{(413\times10^{-9}\ \mathrm{m})}\left(\frac{1\ \mathrm{eV}}{1.60\times10^{-19}\mathrm{J}}\right) - e(2.0\ \mathrm{V}) = 1.0\ \mathrm{eV}$$

Can ask: for this experiment, what is the threshold frequency (or wavelength, λ_t) for ejection of photoelectrons? Defined by relation:

$$K_{\max,\mathrm{t}} = 0 = \frac{hc}{\lambda_t} - \phi \ \Rightarrow\ \lambda_{\mathrm{t}} = \frac{hc}{\phi} = \frac{(6.63\times10^{-34}\ \mathrm{J{\cdot}s})\left(3\times10^{8}\ \frac{\mathrm{m}}{\mathrm{s}}\right)}{(1\ \mathrm{eV})(1.60\times10^{-19}\ \mathrm{J/eV})} = 1.24\times10^{-6}\ \mathrm{m}$$

$\therefore\ \lambda_{\mathrm{t}} = 1240 \text{ nm}.$ For $\lambda > \lambda_{\mathrm{t}}$, photons don’t have enough energy to eject electrons from the metal.

$\Rightarrow$ For $\lambda = 2480\ nm\ (> \lambda_{\mathrm{t}})$ there is no current. No electrons are ejected from the metal.

Lecture Problem 4

An LED emits 1W of optical power at 620 nm. How many photons per second are emitted by the LED?

Lecture Problem 4

Emitted LED power:

$P = E_\gamma \frac{dN_\gamma}{dt}$. (Assuming all photons emitted have same wavelength.)

$$\frac{dN_\gamma}{dt} = \frac{P}{E_\gamma} = \frac{P}{\left(\frac{hc}{\lambda}\right)} = \frac{P\,\lambda}{hc} = \frac{(1.0\ \mathrm{W})(620\times10^{-9}\ \mathrm{m})}{(6.63\times10^{-34}\ \mathrm{J{\cdot}s})\left(3\times10^{8}\frac{\mathrm{m}}{\mathrm{s}}\right)} = 3.12\times10^{18}\ \mathrm{s}^{-1}\ .$$