Welcome to Quantum Mechanics 1

- "The most important fundamental laws and facts have all been discovered, and these are so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote. ... Our future discoveries must be looked for in the sixth place of decimals."

  Albert A. Michelson (1894)

Welcome to Quantum Mechanics 2

- "The most important fundamental laws and facts have all been discovered, and these are so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote. ... Our future discoveries must be looked for in the sixth place of decimals."

  Albert A. Michelson (1894)

- "I cannot seriously believe in the quantum theory..."

  Albert Einstein

Welcome to Quantum Mechanics 3

- "The most important fundamental laws and facts have all been discovered, and these are so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote. ... Our future discoveries must be looked for in the sixth place of decimals."

  Albert A. Michelson (1894)

- "I cannot seriously believe in the quantum theory..."

  Albert Einstein

- "The more success the quantum theory has the sillier it looks."

  Albert Einstein

Mysteries that Quantum Mechanics Explained 4

- Spectral lines
- Photoelectric effect
- Specific heat of diatomic gases freeze-out
- Constant specific heat of metals
- Blackbody radiation
- Compton effect
- Davisson-Germer
- Radioactivity
- Atomic structure/nuclear physics
- Why does the Sun shine?

The current list:

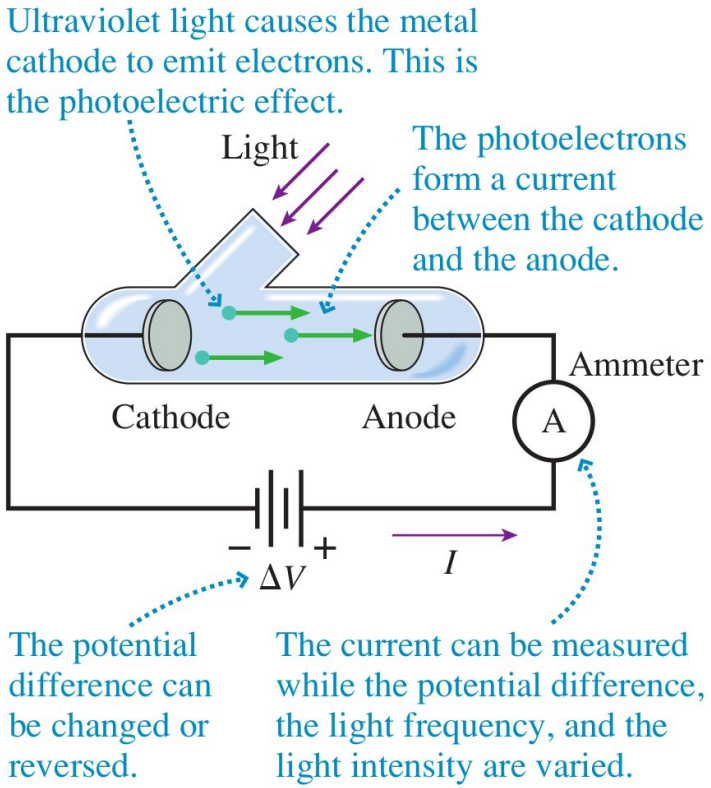
`https://en.wikipedia.org/wiki/List_of_unsolved_problems_in_physics`

Some Metals Like It Hot (and some don't care). 5

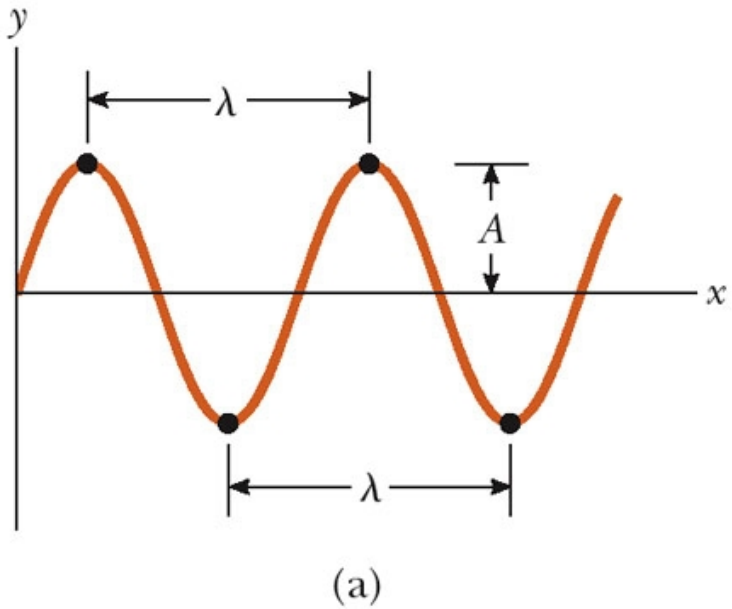
Light transfers energy. The figure shows a device to measure this energy flow from a metal due to the photoelectric effect. The Poynting vector describes the intensity

$$\vec{S} = \frac{1}{\mu_0}\vec{E} \times \vec{B}$$

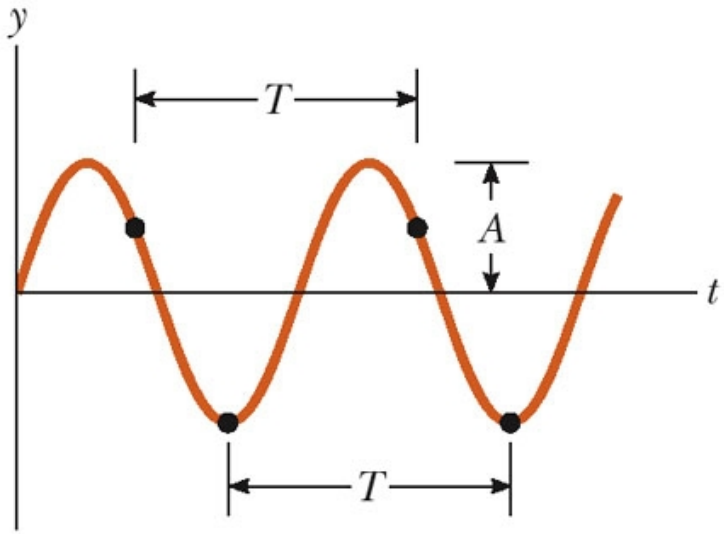
where $\vec{E}$ and $\vec{B}$ are oscillating electric and magnetic fields. Electrons are ejected from the surface with energy E_{ej}. Assume all the light energy falling on the surface atom goes into a single electron. What is the rate of ejected electrons? What is the time lag between when light first strikes the surface and the first electron is ejected?



Waves 6



(a)



(b)

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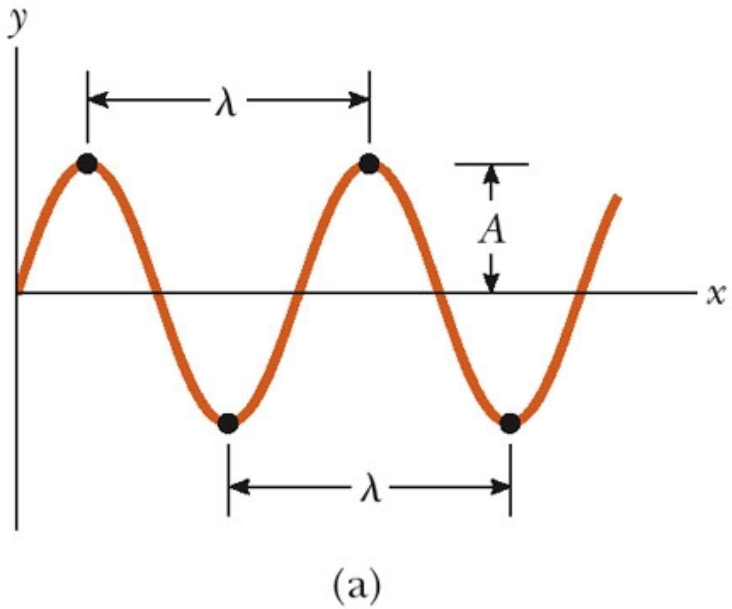
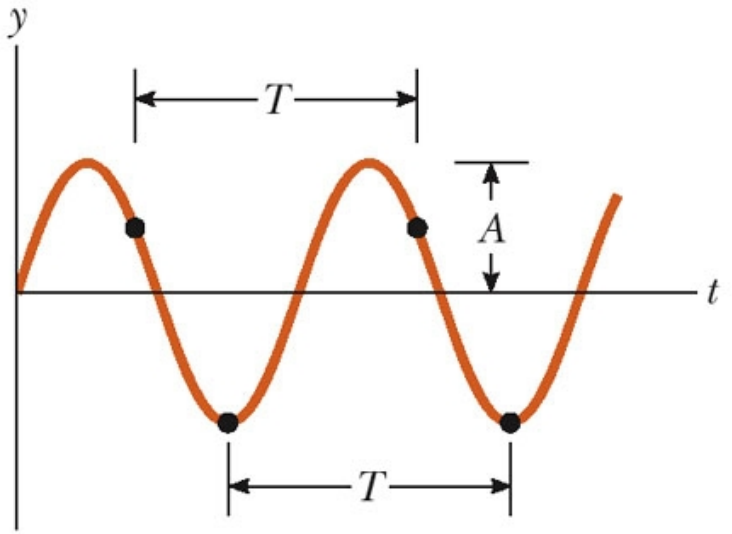
- Demo is here.



(a)



(b)

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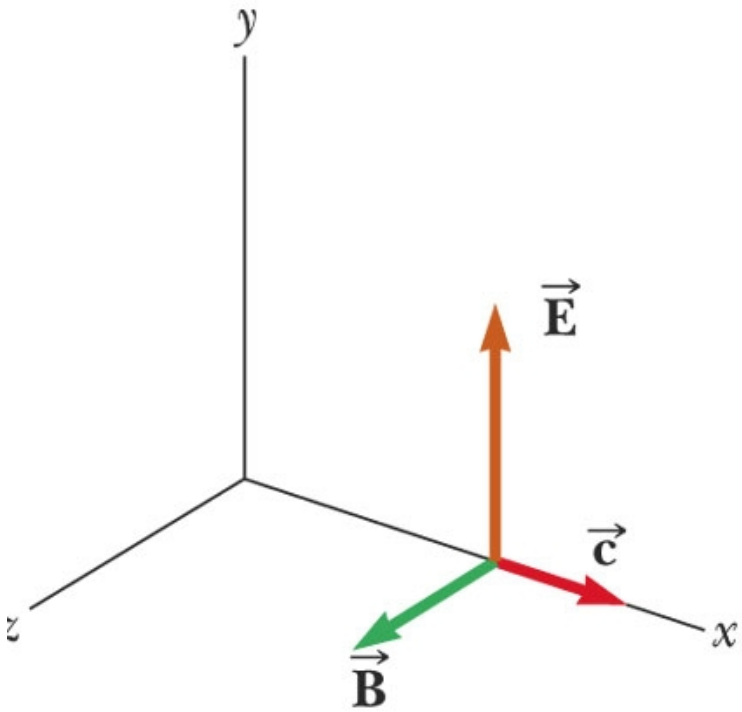
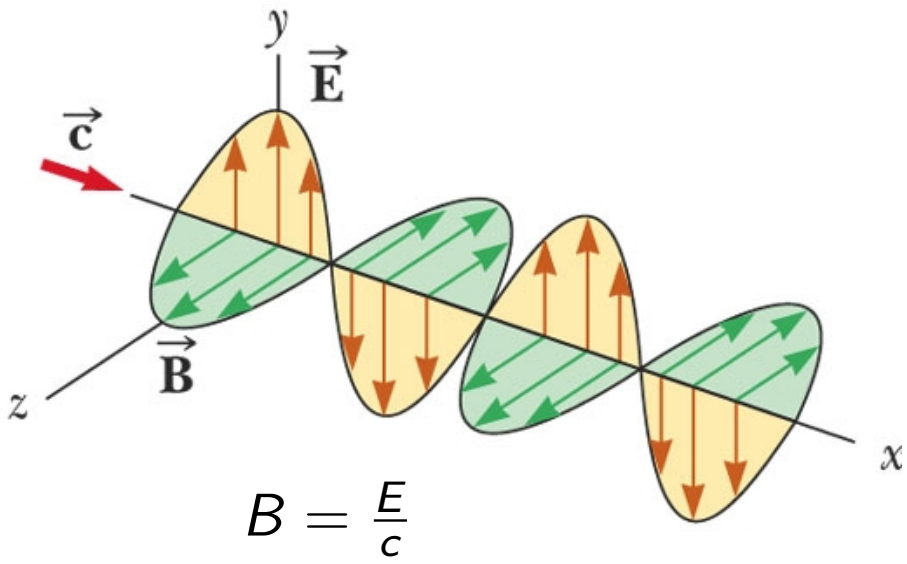
- Demo is here.
- Disturbance that moves.
- Transmits energy and momentum.
- Delocalized - waves spread out.
- Superposition - waves add.
- Features: T, f, λ, A, v
- $y(x,t) = A\sin(kx - \omega t + \phi_0)$

Electromagnetic Waves 8



(a)



$B = \frac{E}{c}$

(b)

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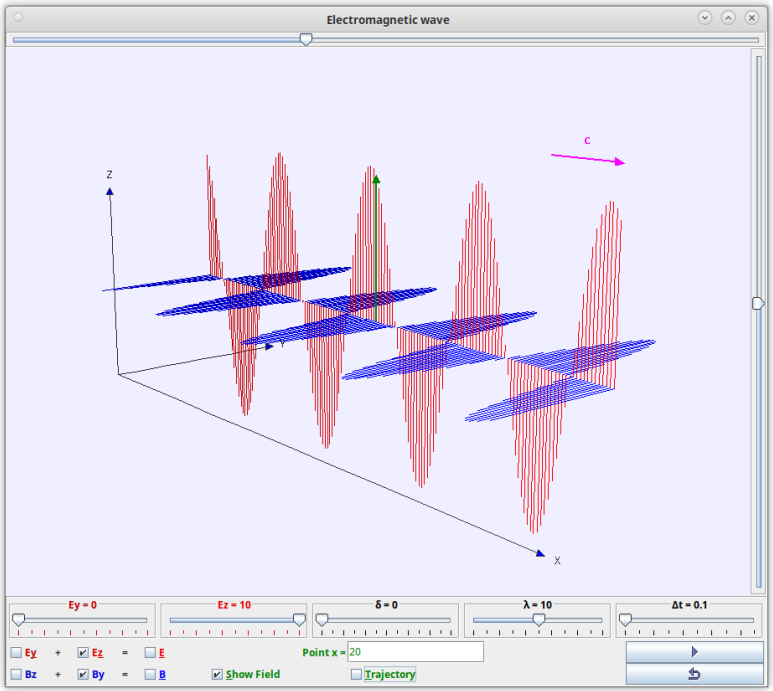
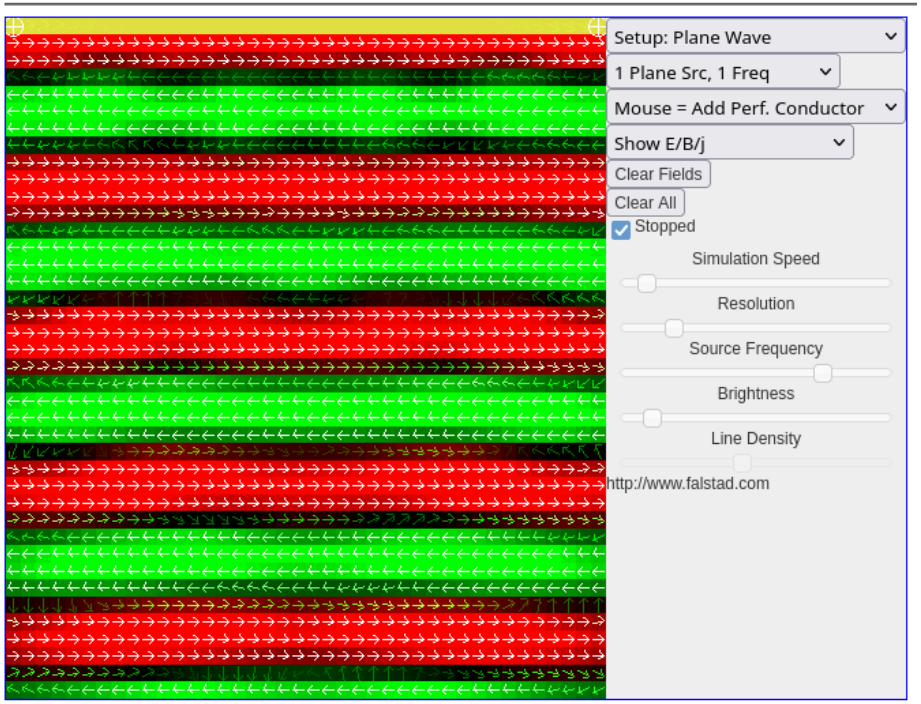
The simulations are here and here.

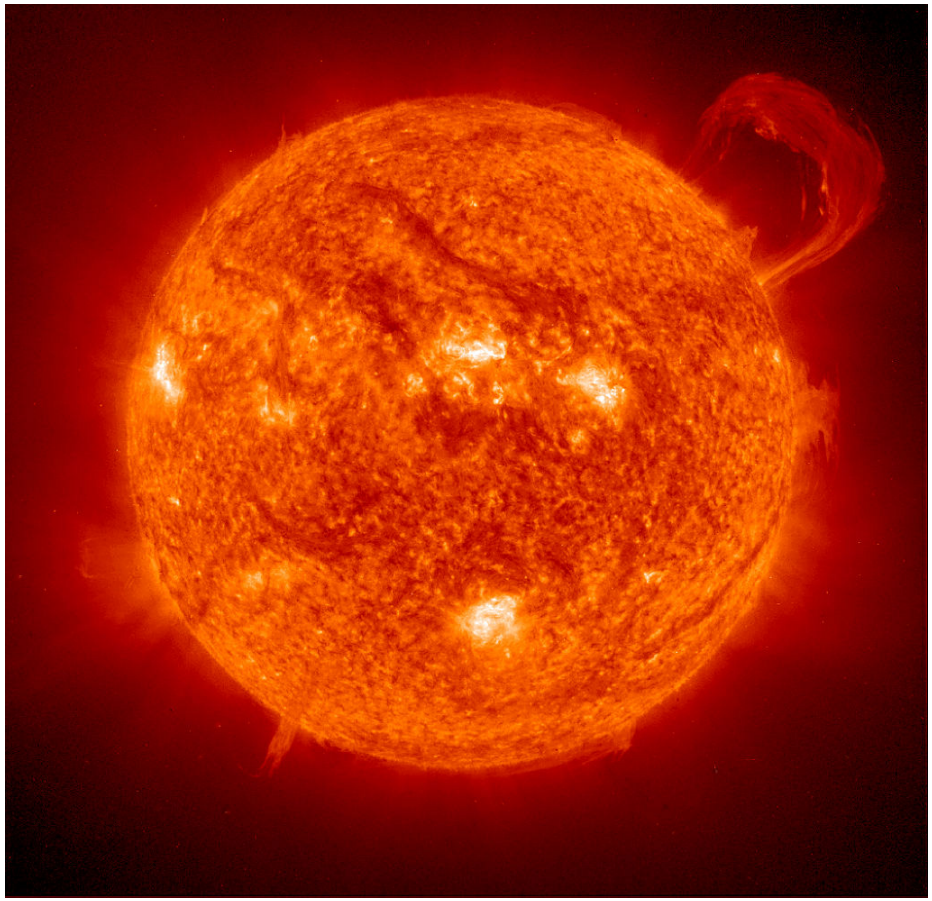
Electromagnetic Waves on the Move 9





The Electric Field of Sunlight 10

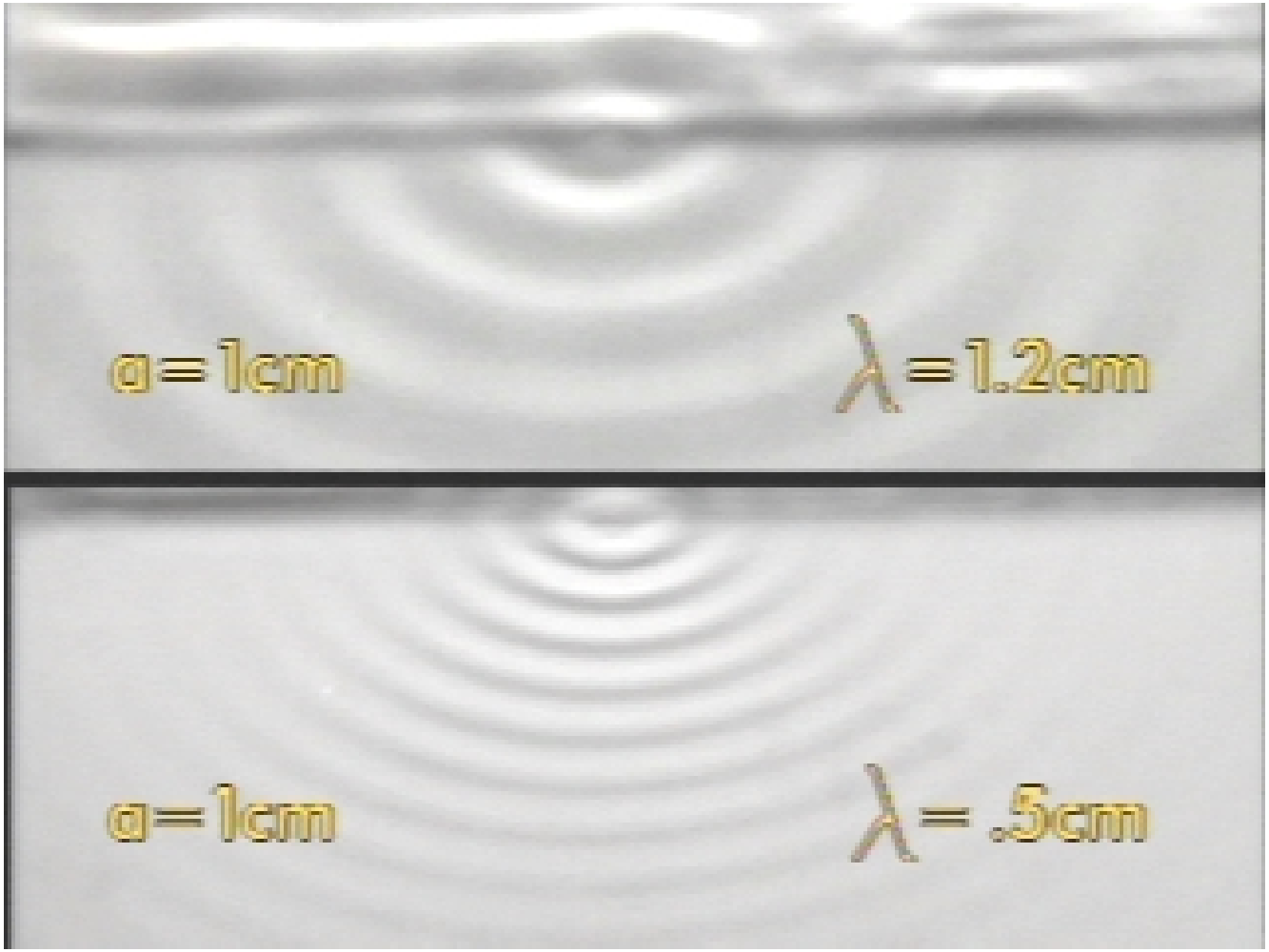
The intensity of sunlight reaching the Earth is called the solar constant (which is not really constant) and has a value of $I_s = 1366\ J/s - m^2$. What is the size of the electric field in sunlight? How does this compare with the typical fields we use in lab ($|\vec{E}| \approx 10\ N/C$)?



What Happens When Waves Hit Holes? 11

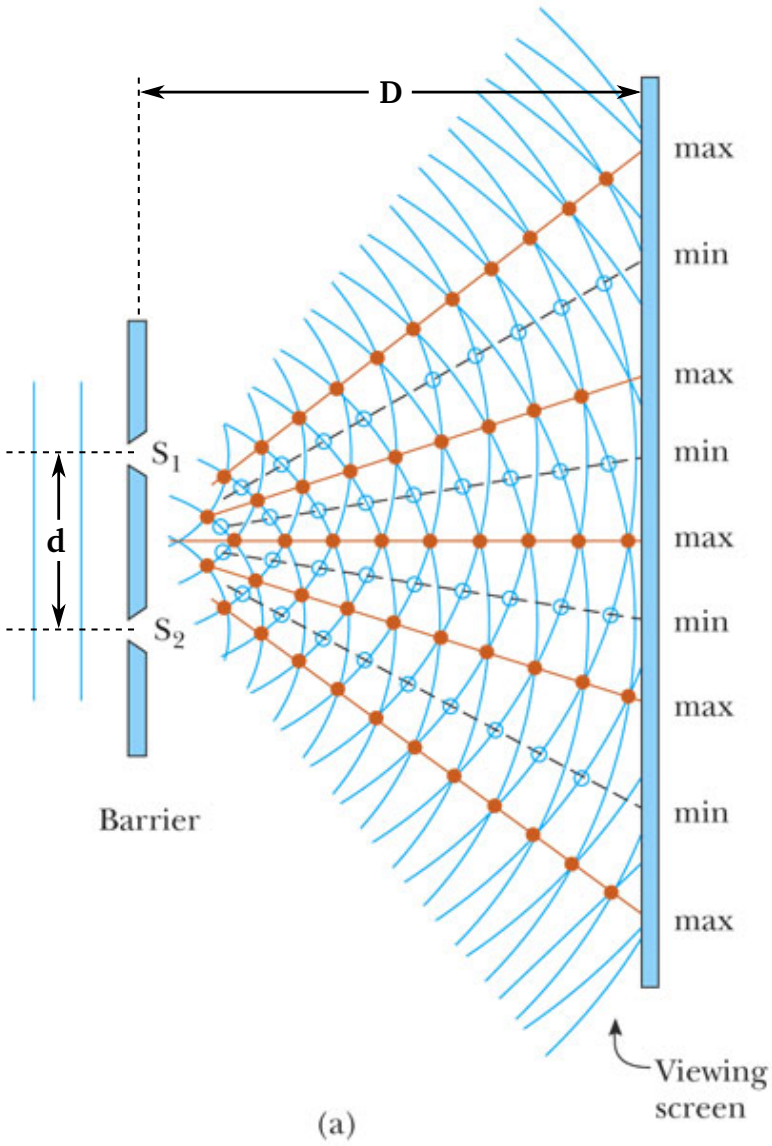
The videos are here and here. The simulation is here.

What Happens When Waves Hit Holes? 12

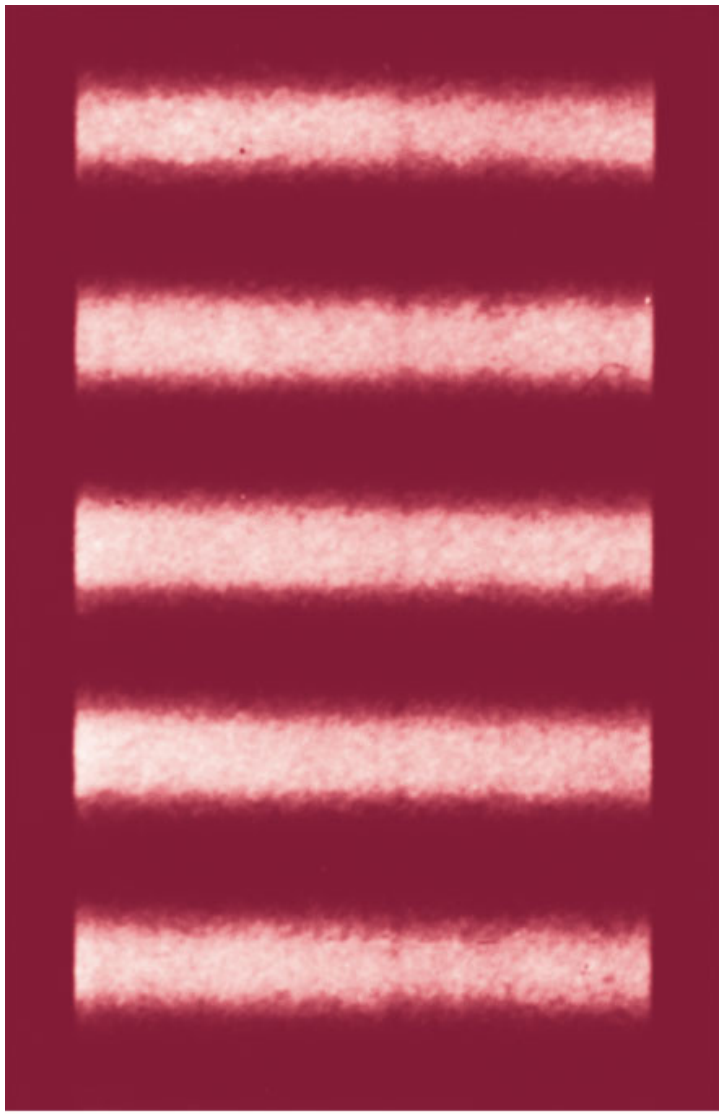


The videos are here and here. The simulation is here.

Double Slit Interference - 1 13



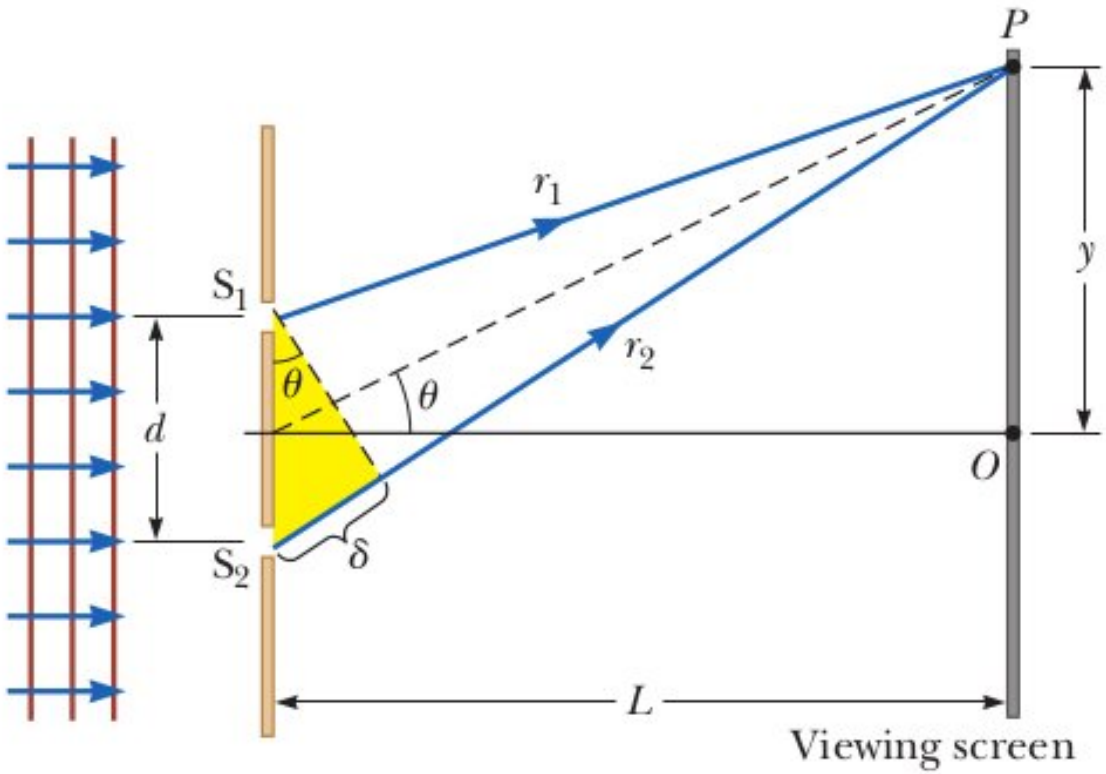
(a)



(b)

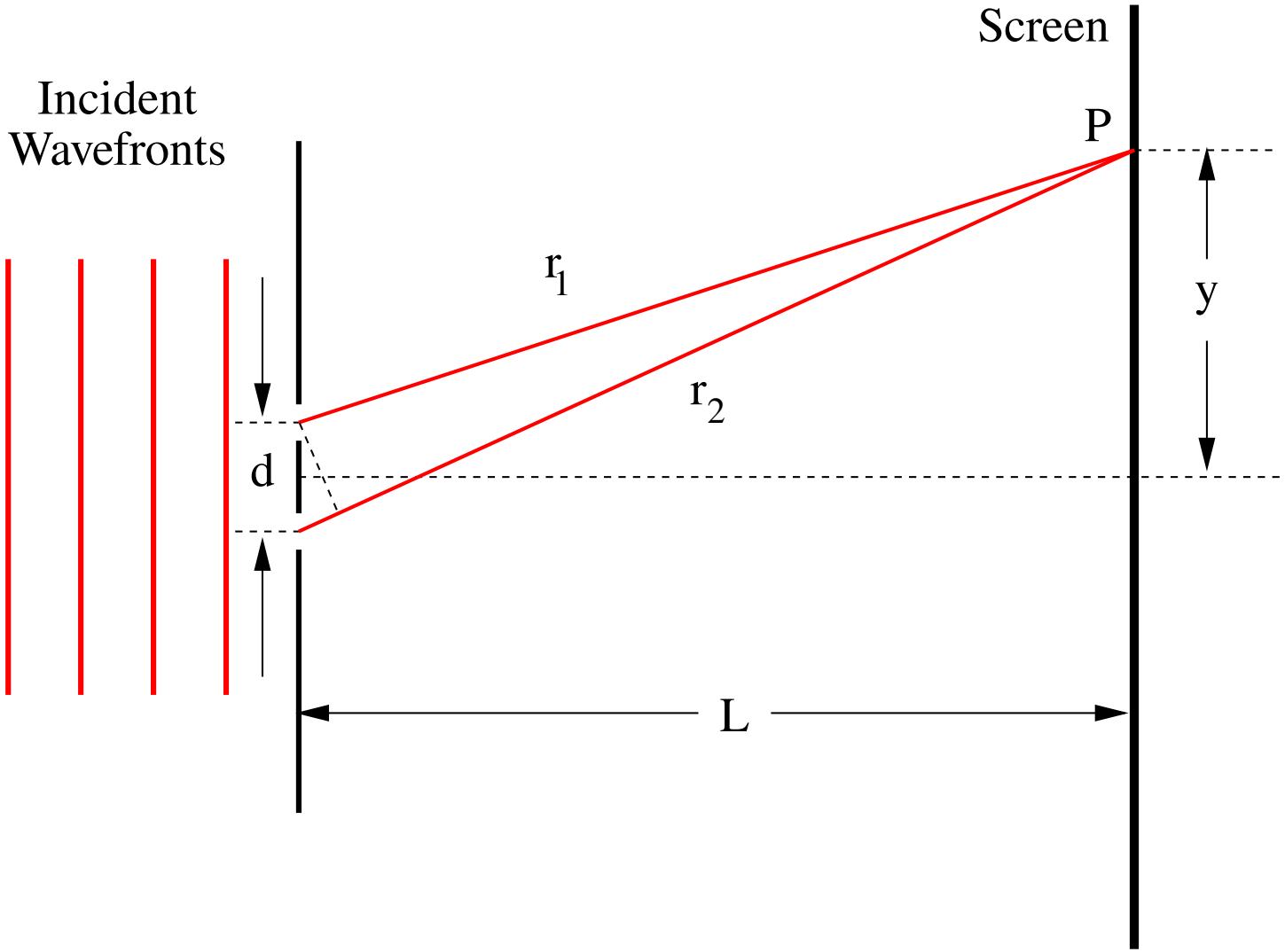
Double Slit Interference - 2 14

A double-slit experiment is performed with $\lambda = 589\ nm$ light and a distance $L = 2.0\ m$ between the slits and the screen. The fifth interference maximum is observed at a distance $y = 4.0\ mm$ from the central maximum. What is the spacing d of the slits?

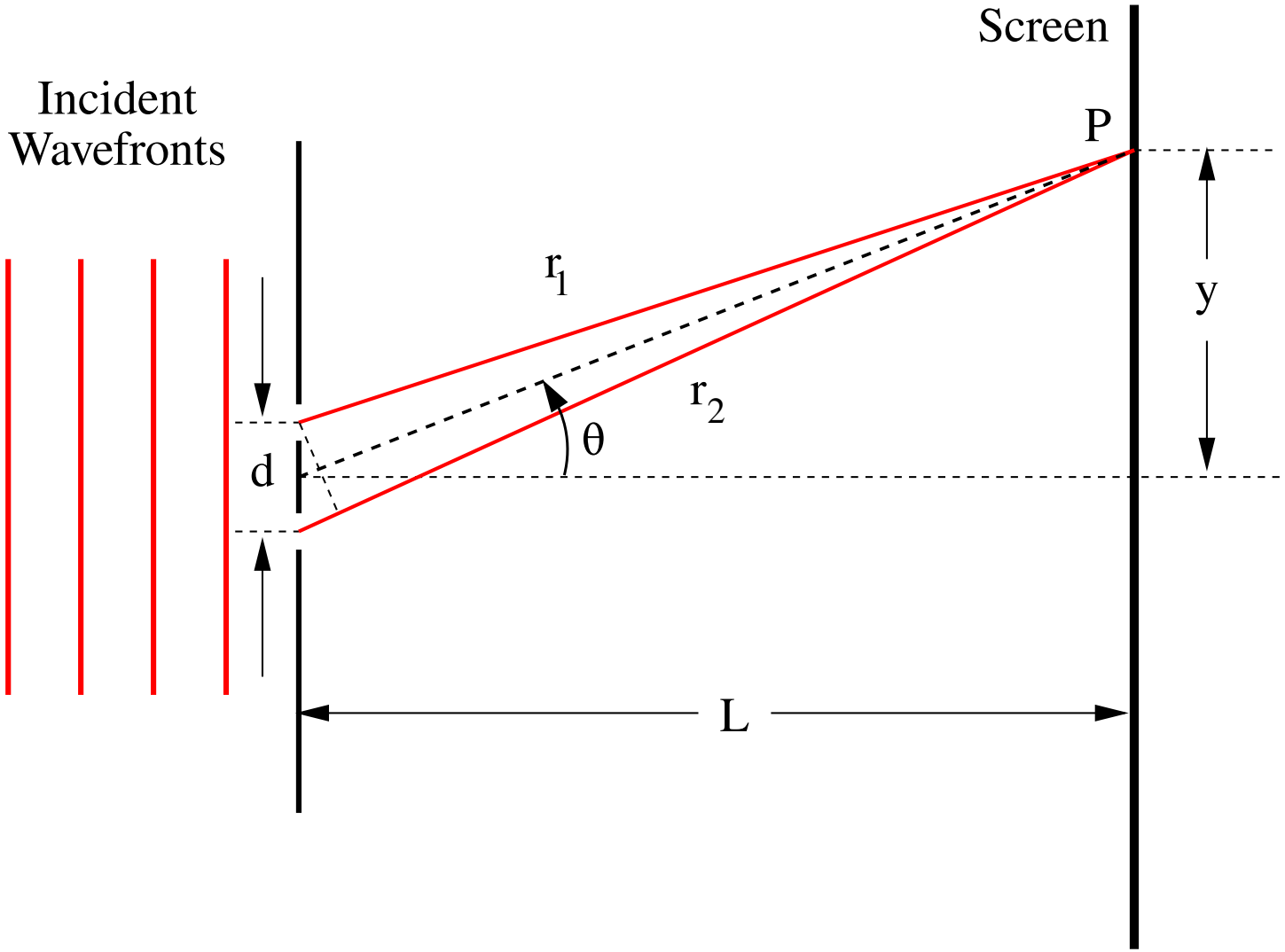


The simulation is here.

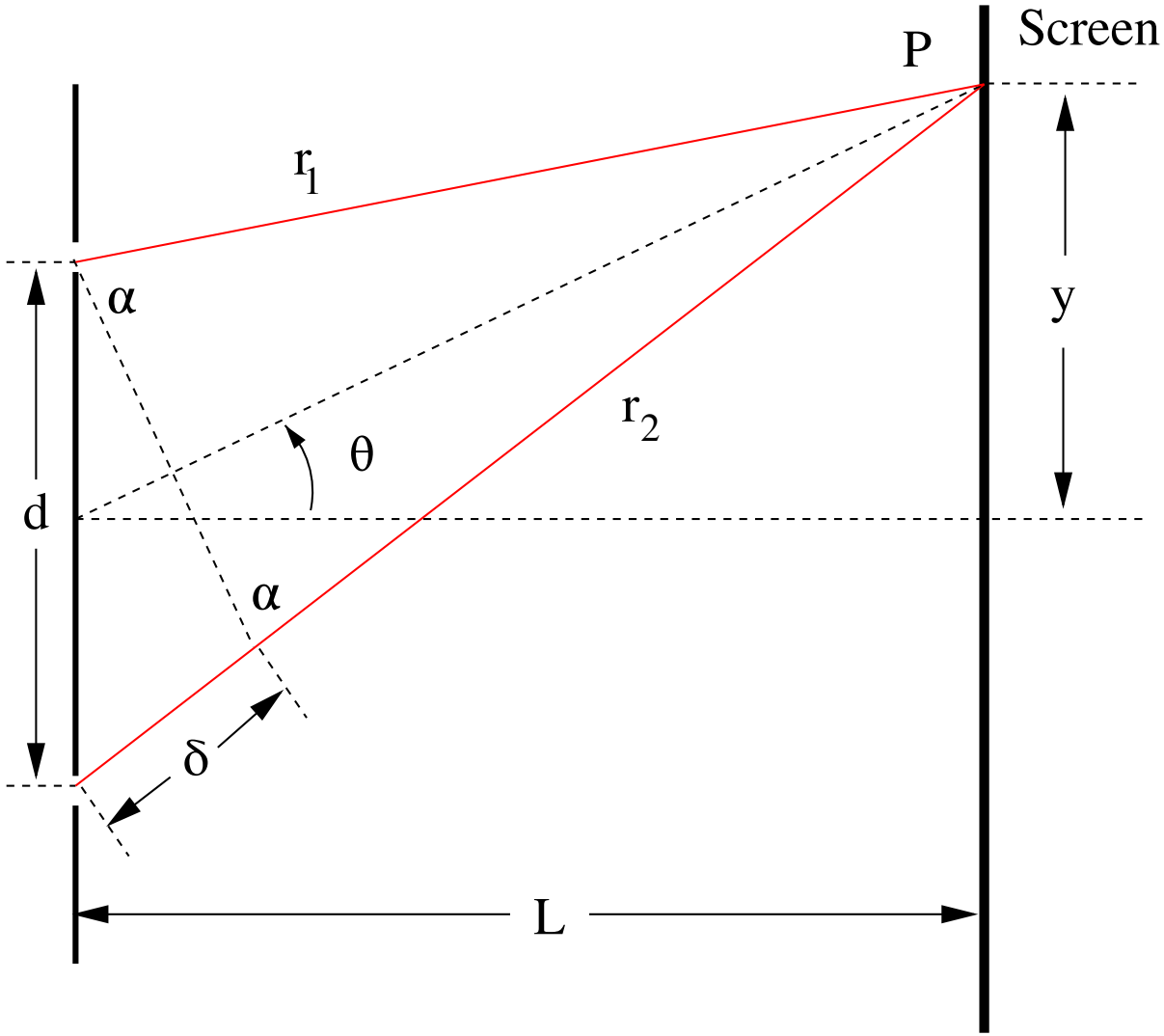
Double Slit Interference



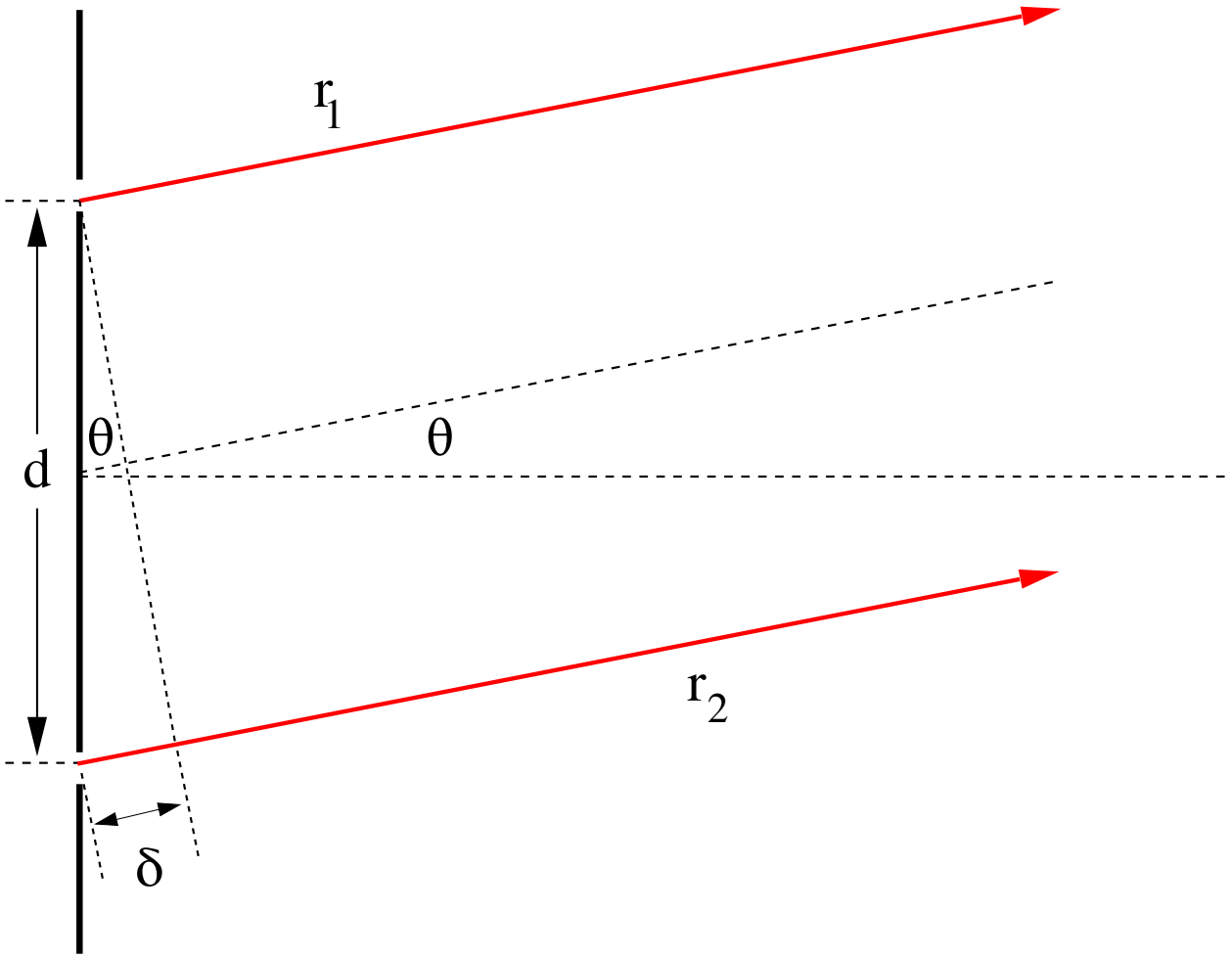
Double Slit Interference



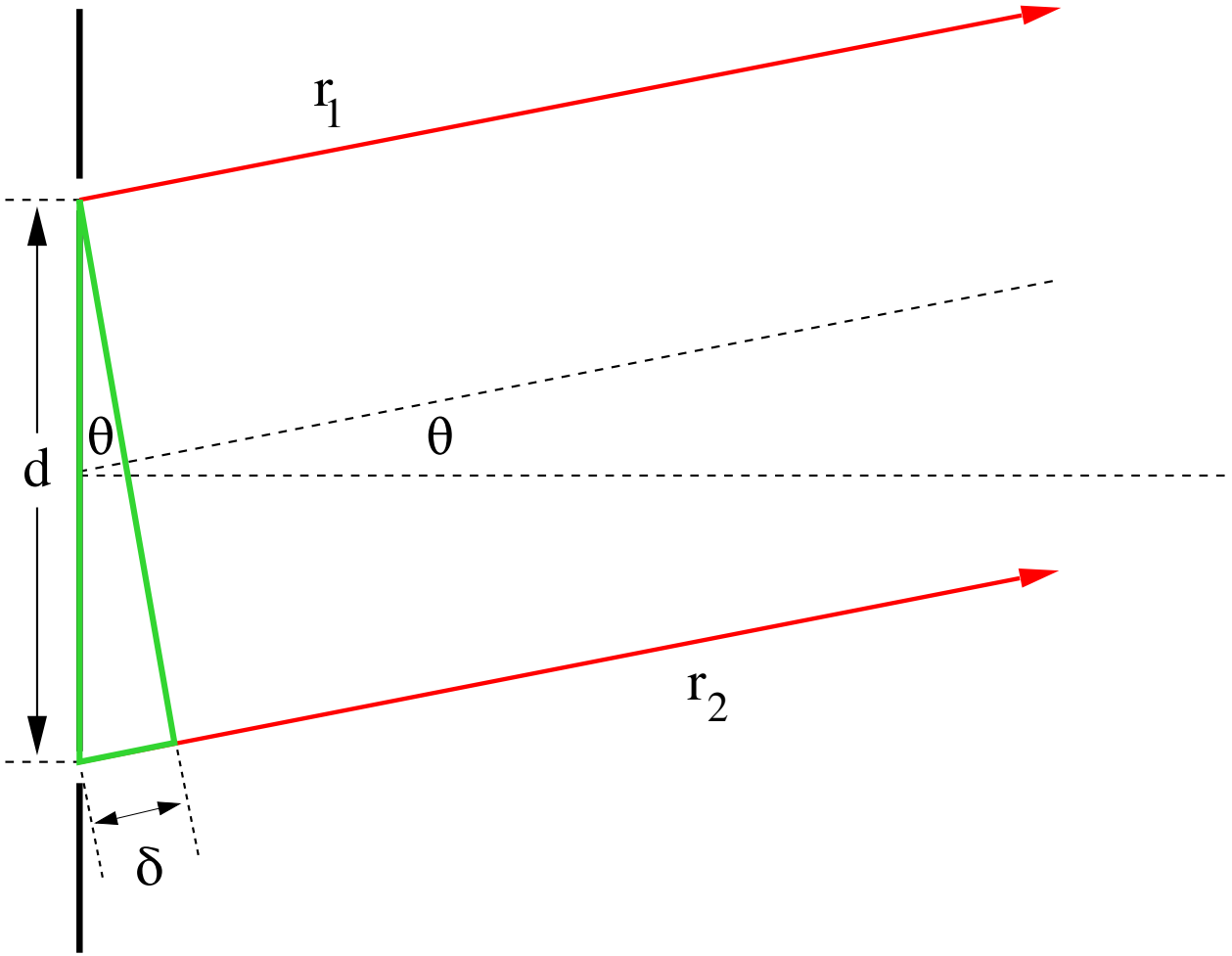
Double Slit Interference



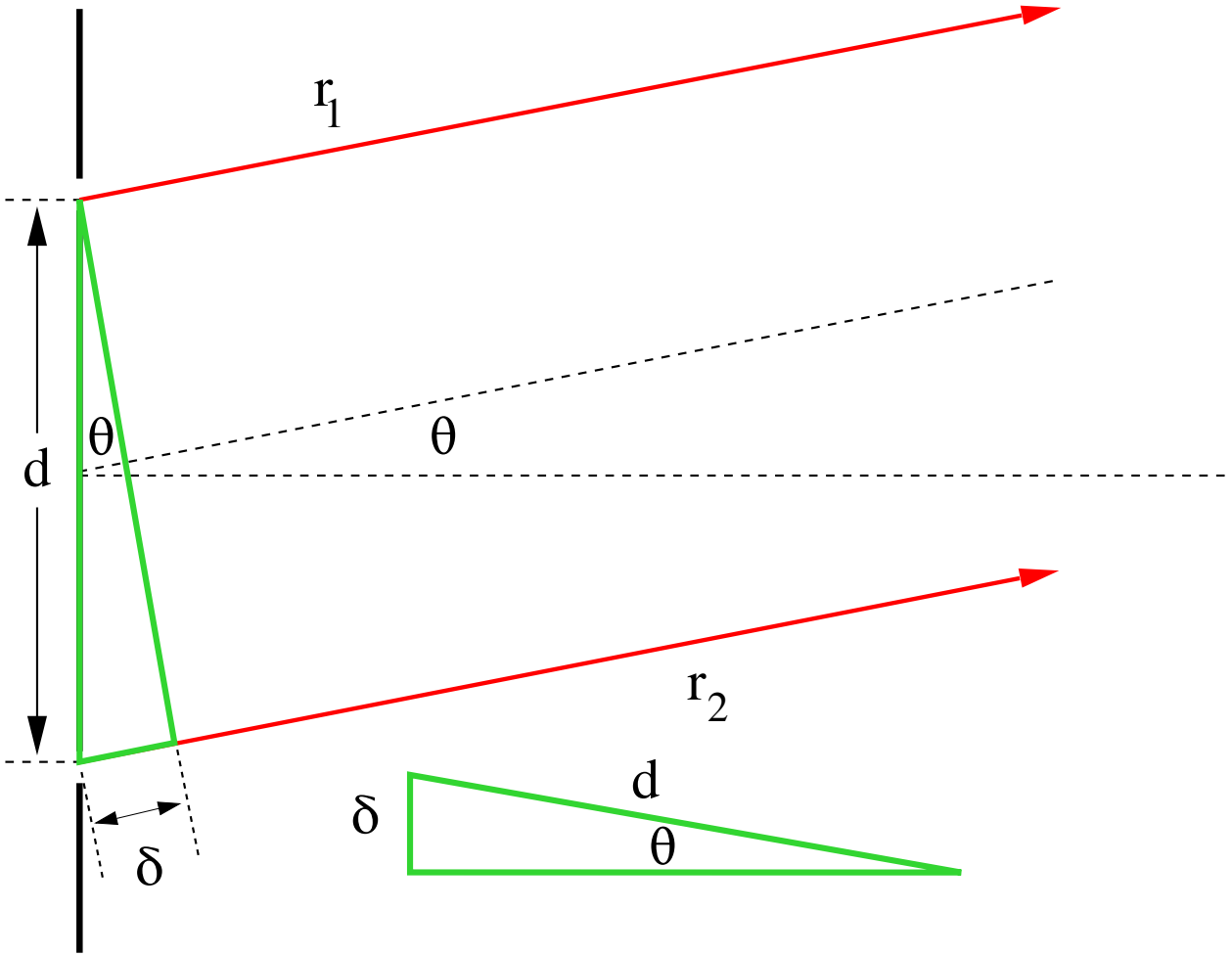
Double Slit Interference

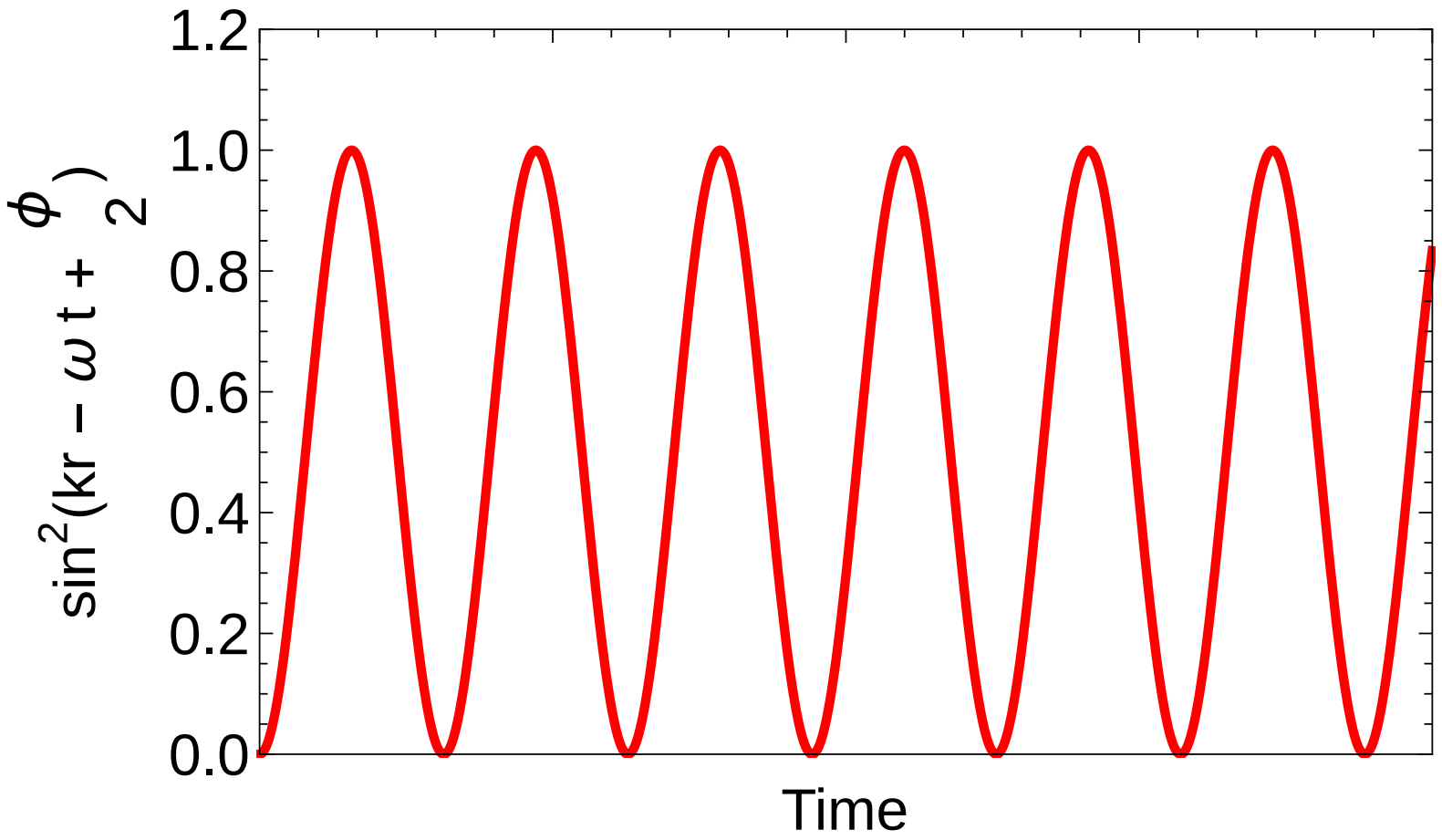


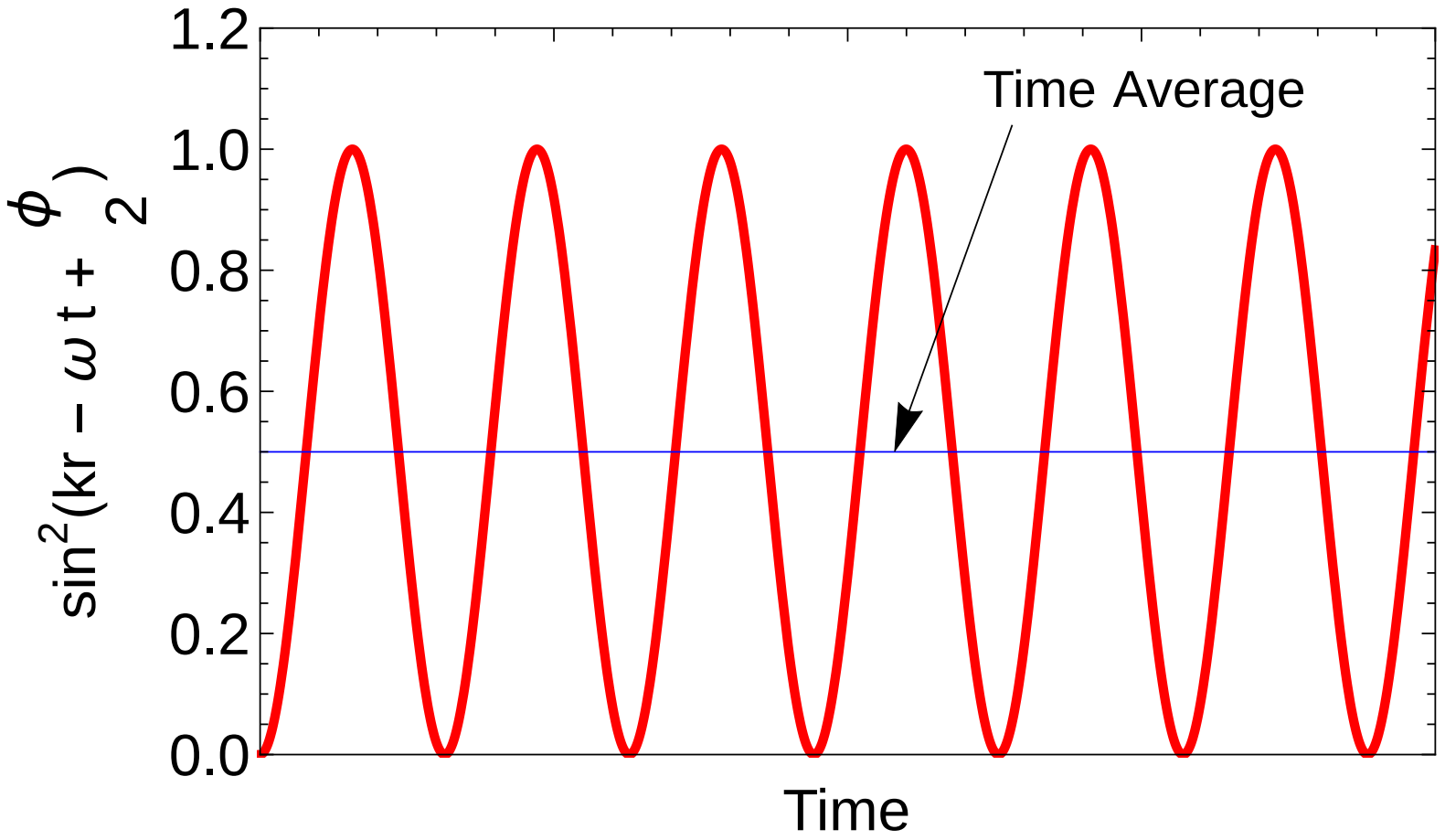
Double Slit Interference



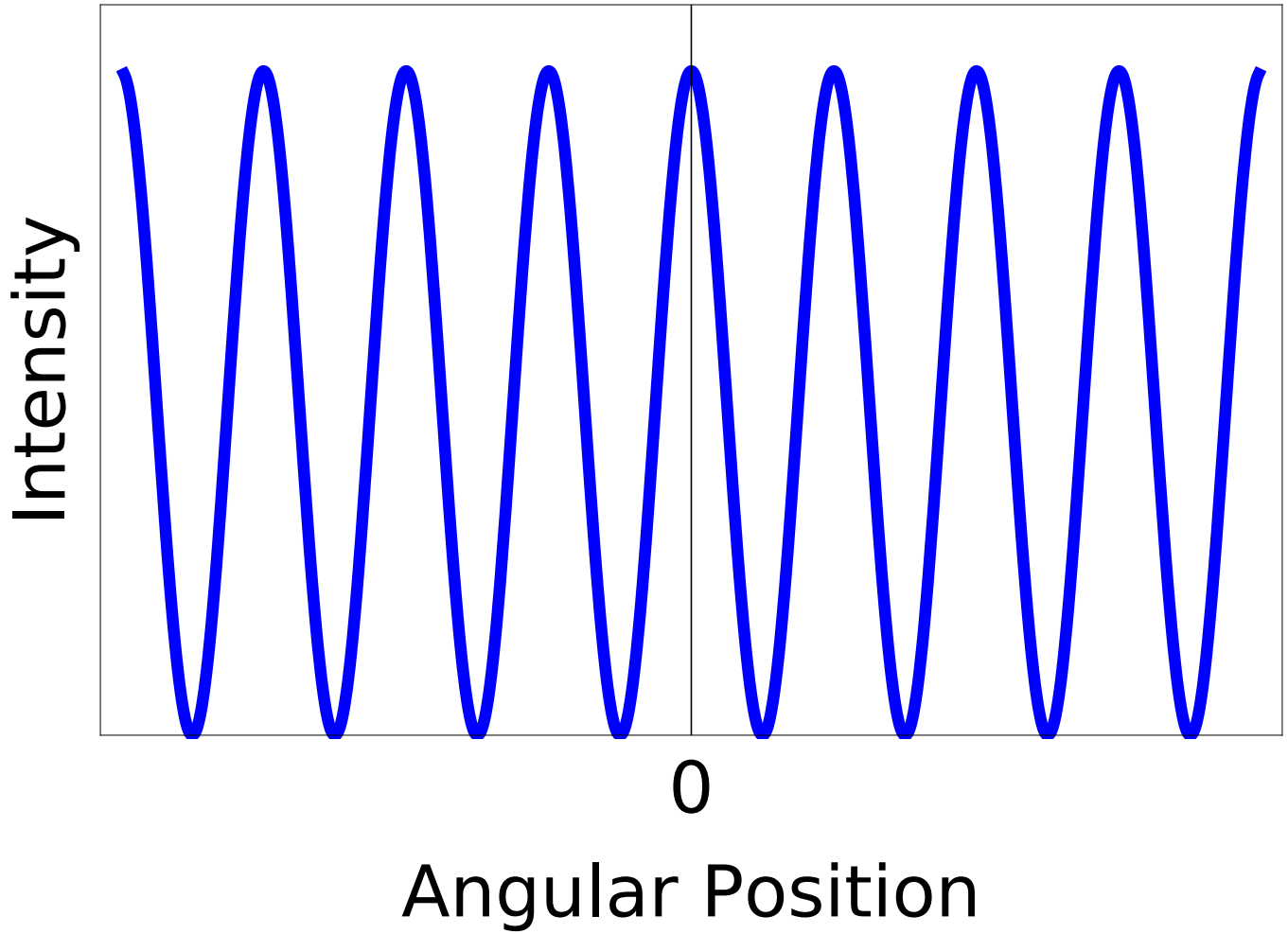
Double Slit Interference




1.2
1.0
0.8
0.6
0.4
0.2
0.0
$\sin^2(kr - \omega t + \frac{\phi}{2})$
Time

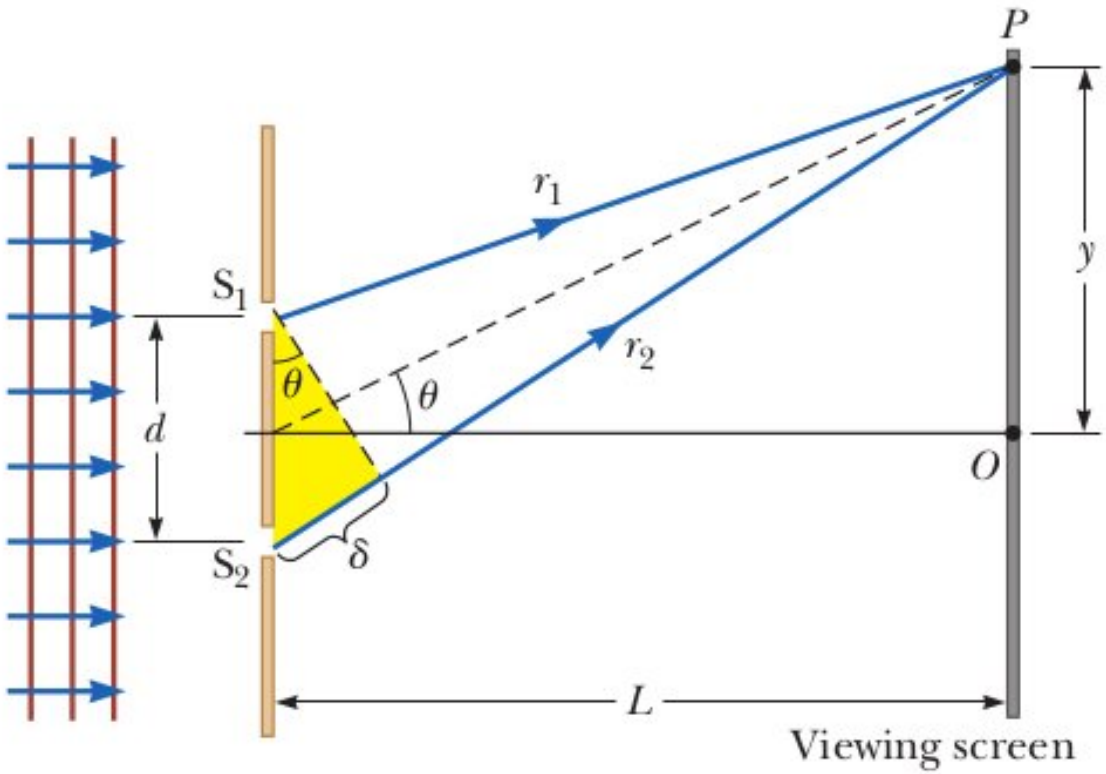

1.2
1.0
0.8
0.6
0.4
0.2
0.0
Time Average
$\sin^2(kr - \omega t + \frac{\phi}{2})$
Time

Predicted Double Slit Interference Pattern 23



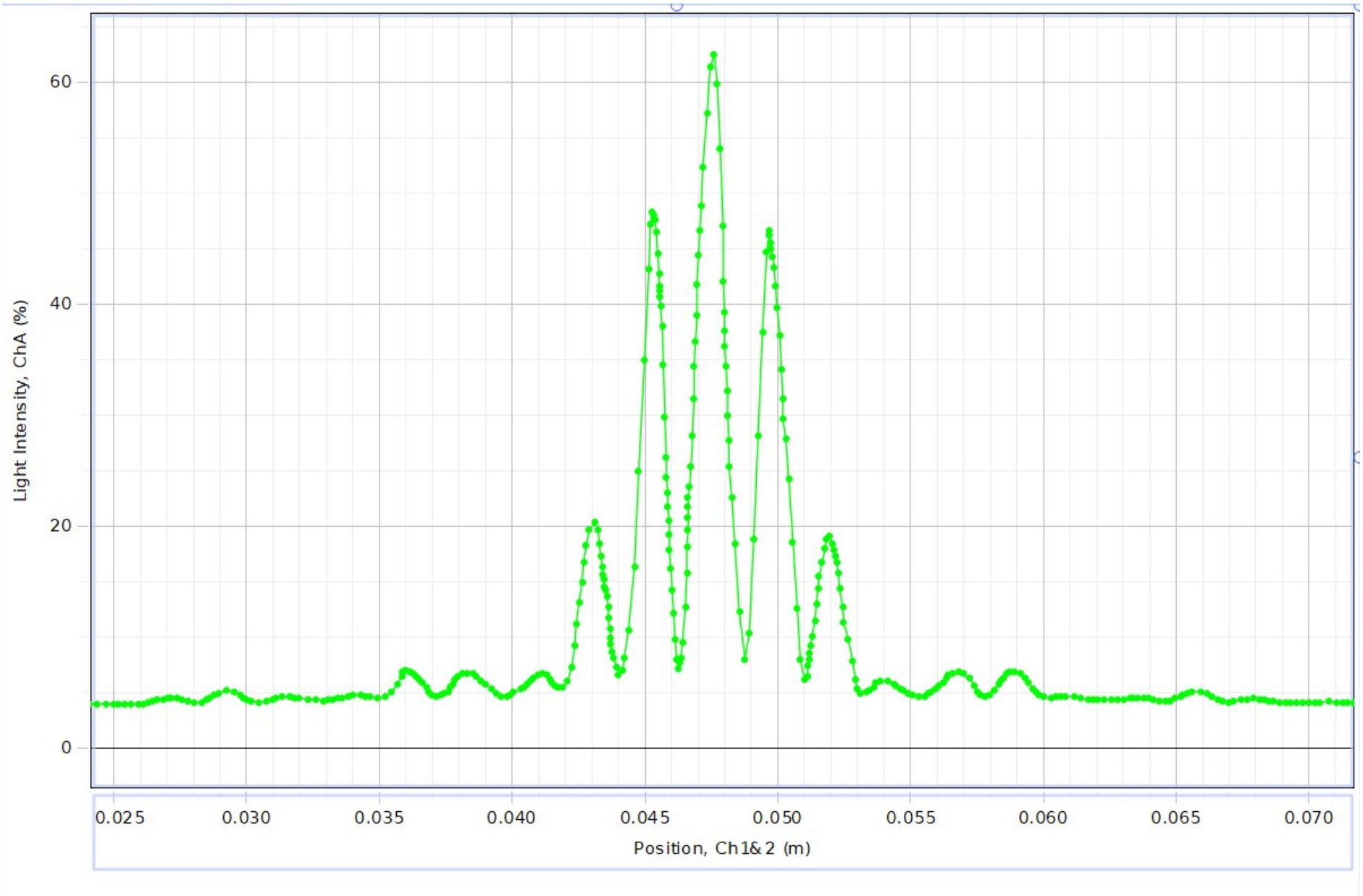
Double Slit Interference - 2 24

A double-slit experiment is performed with $\lambda = 589\ nm$ light and a distance $L = 2.0\ m$ between the slits and the screen. The fifth interference maximum is observed at a distance $y = 4.0\ mm$ from the central maximum. What is the spacing d of the slits?

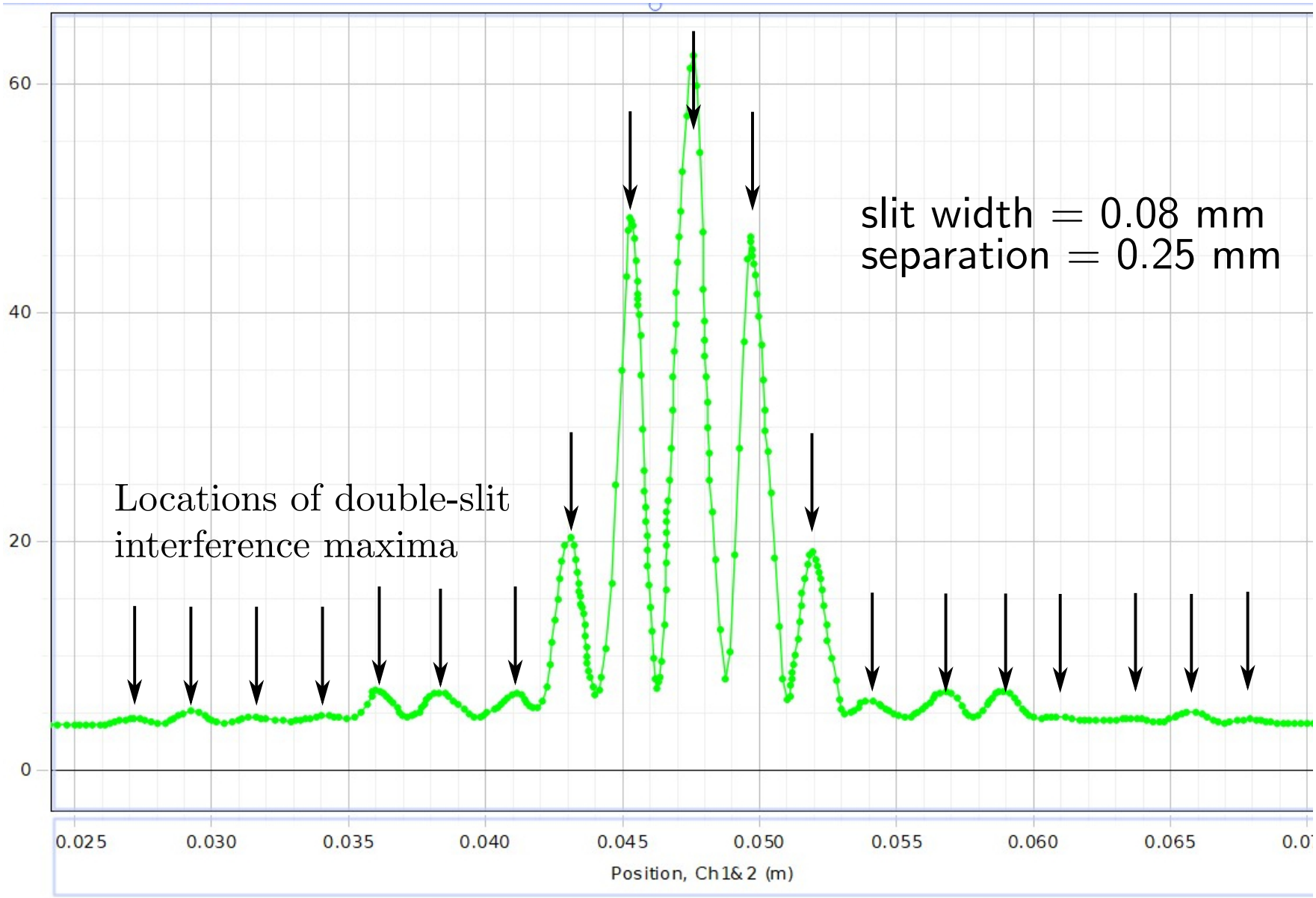


The simulation is here.

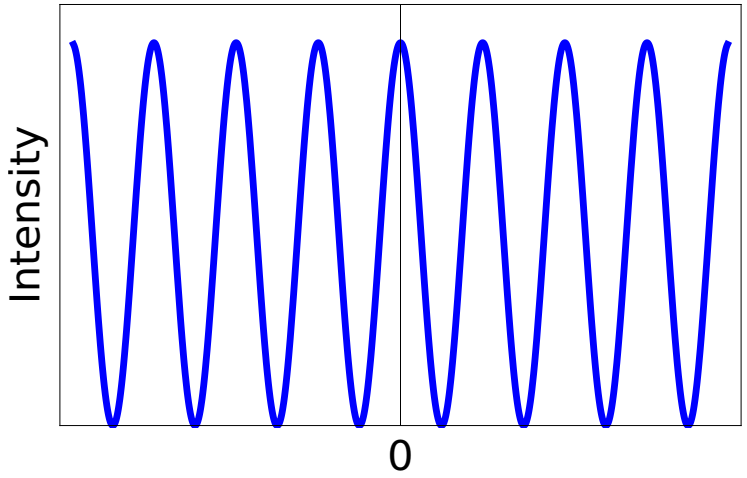
Measured Double Slit Interference Pattern 25

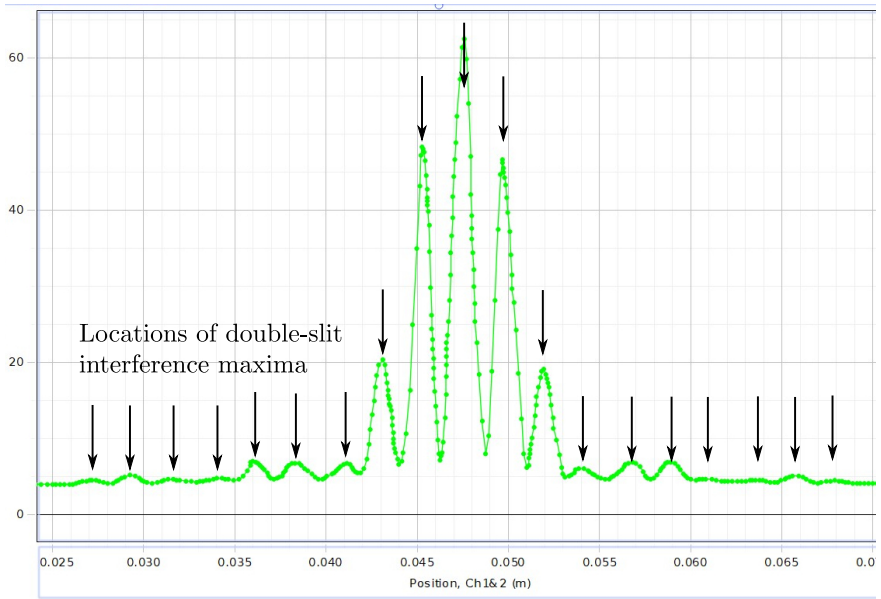


Measured Double Slit Interference Pattern 26

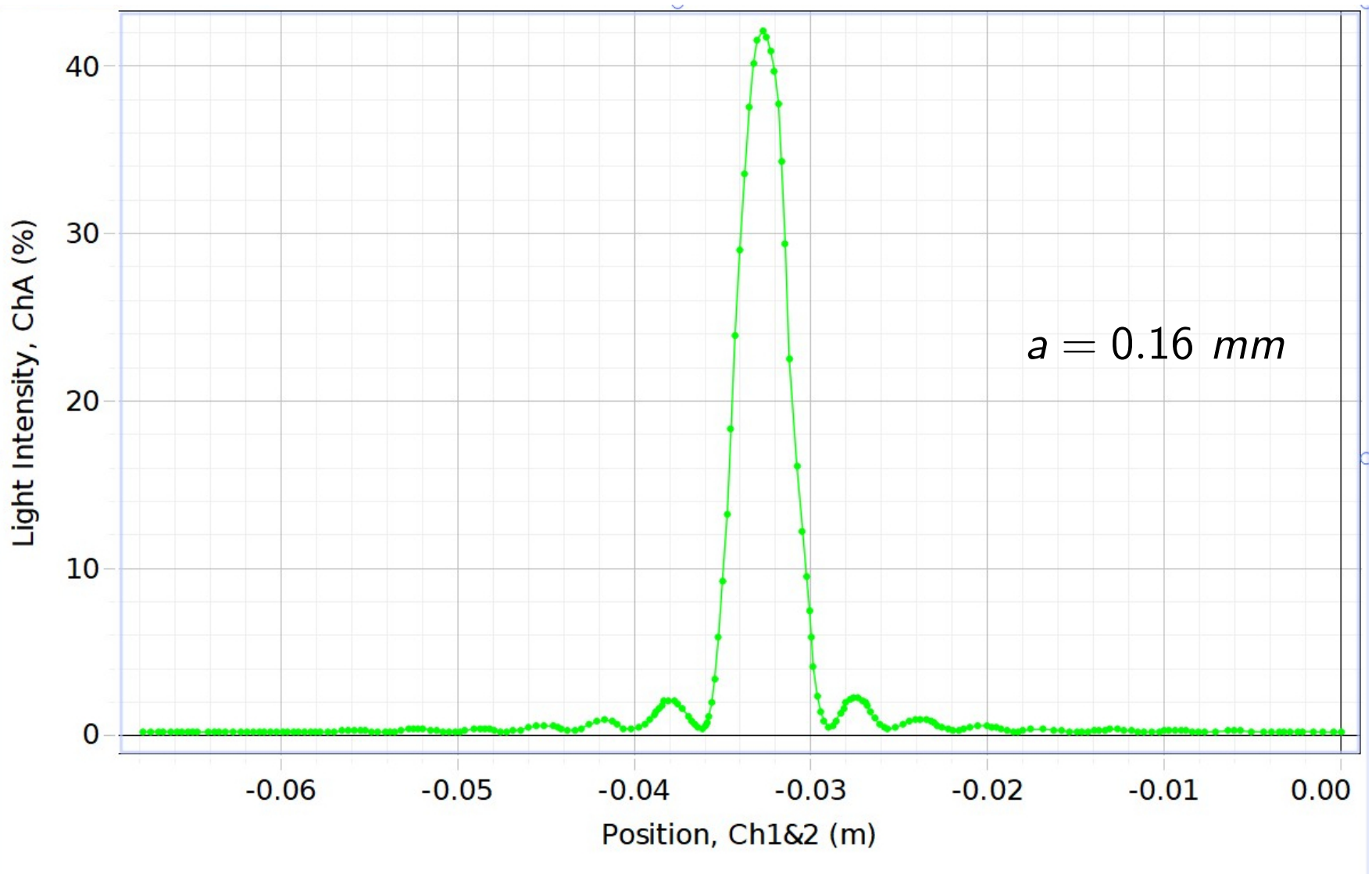


Double Slit Interference Intensity Pattern 27



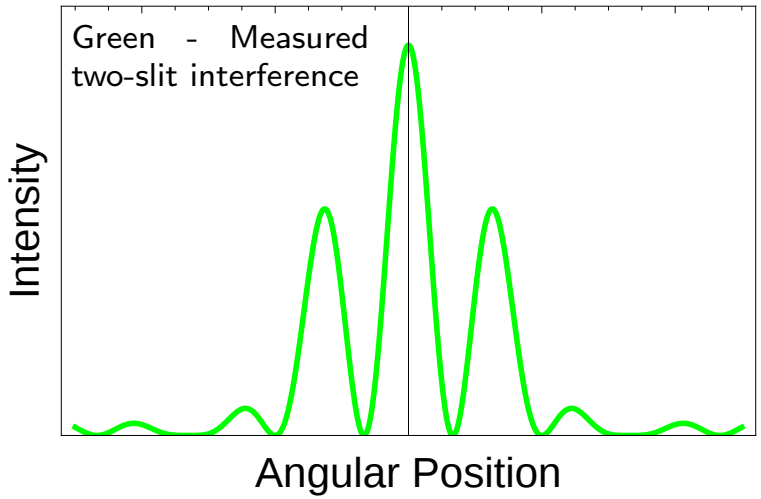


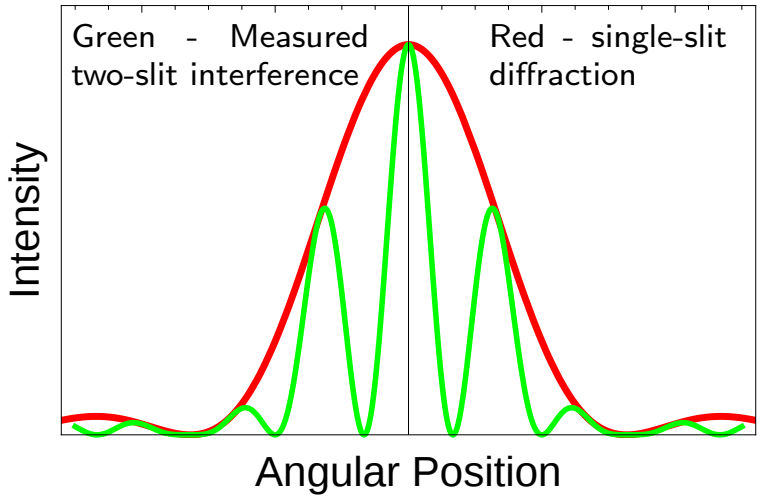
Diffraction At a Single Slit 28



The simulation is here.

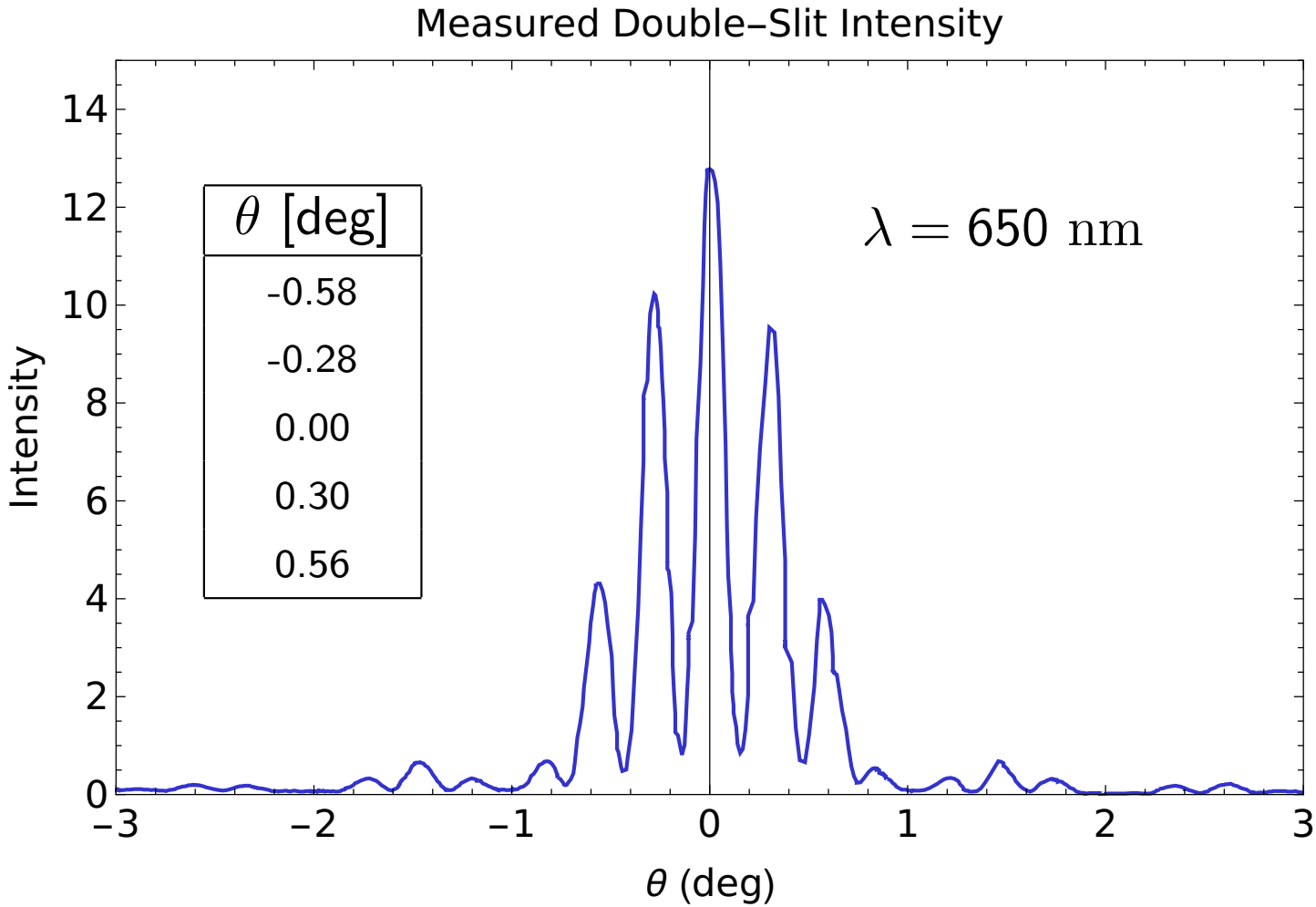
Interference and Diffraction Together 29





Unraveling Diffraction and Interference 30

A double slit interference pattern is shown below. The angular distance of the closest bright spots to the central peak is shown in the inset. What is the separation between the slits? What is the size of the each slit?

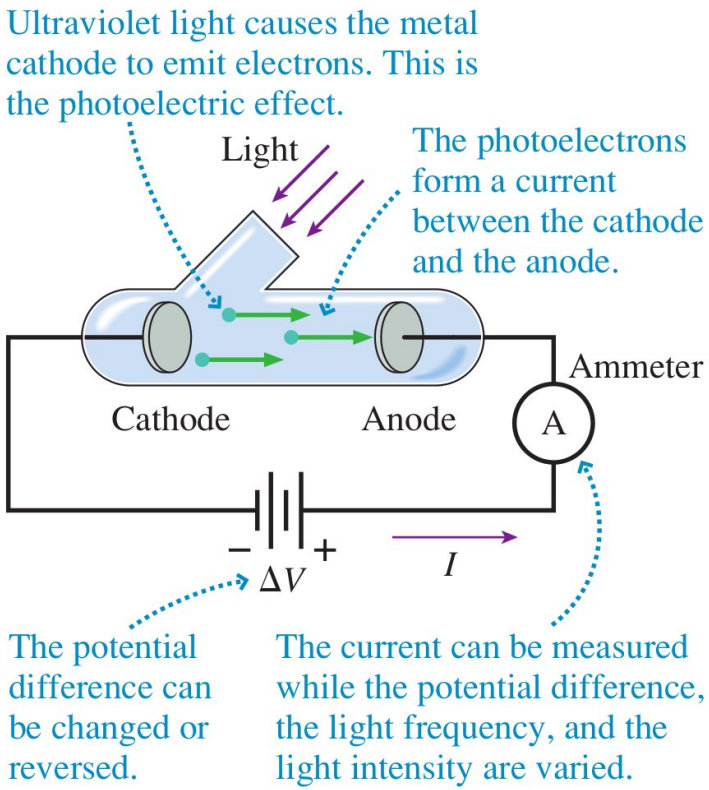


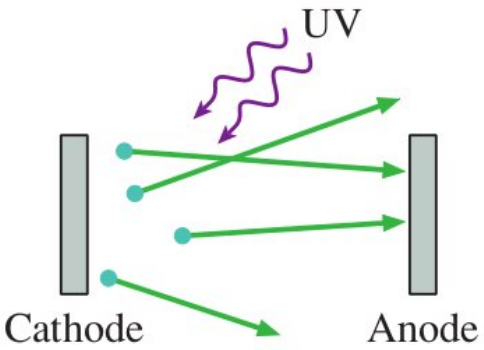
Some Metals Like It Hot (and some don't care). 31

Light transfers energy. The figure shows an apparatus to measure the energy flow from a metal due to the photoelectric effect. The intensity of light is described by the Poynting vector

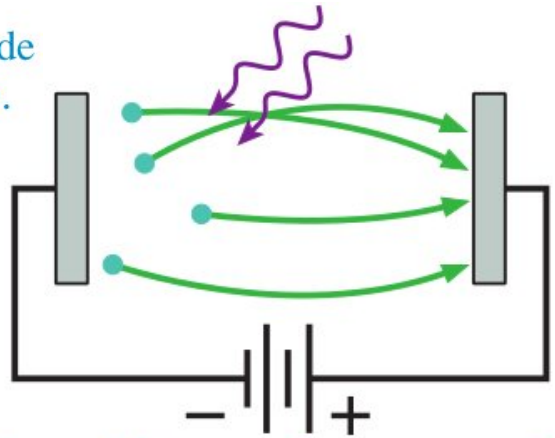
$$\vec{S} = \frac{1}{\mu_0}\vec{E} \times \vec{B}$$

where $\vec{E}$ and $\vec{B}$ are oscillating electric and magnetic fields. Electrons are ejected from the surface. Assume the minimum energy to eject an electron is E_{ej} and the light intensity falling on a surface atom goes into a single electron. What is the rate of ejected electrons? What is the time lag between when light first strikes the surface and the first electron is ejected?

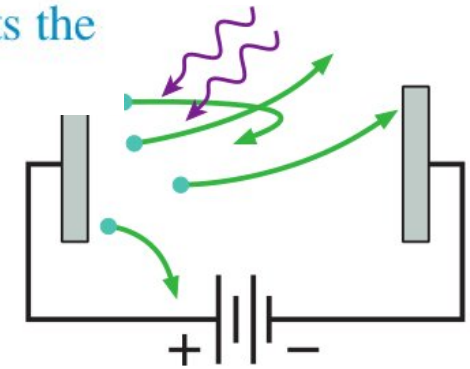




$\Delta V = 0$: The photoelectrons leave the cathode in all directions. Only a few reach the anode.

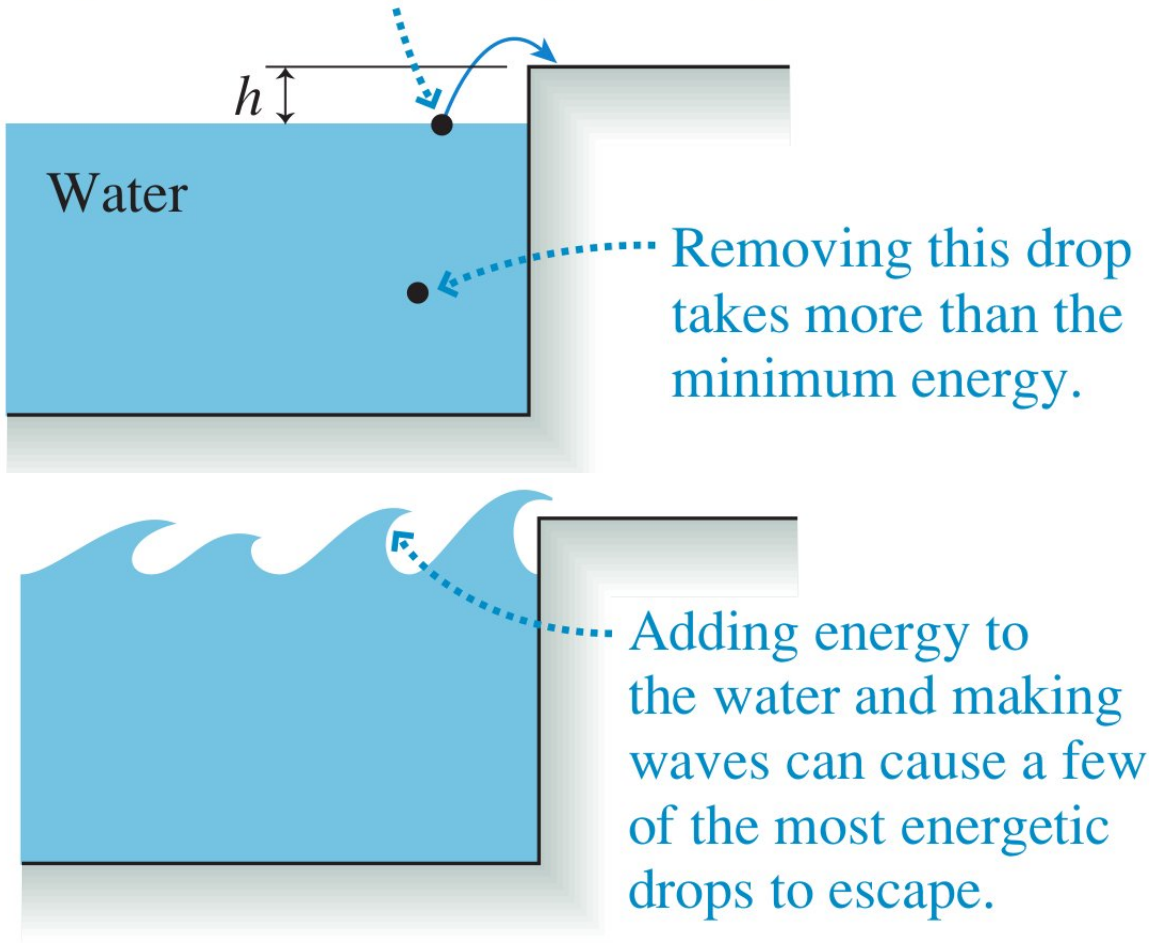


$\Delta V > 0$: A positive anode attracts the photoelectrons to the anode.



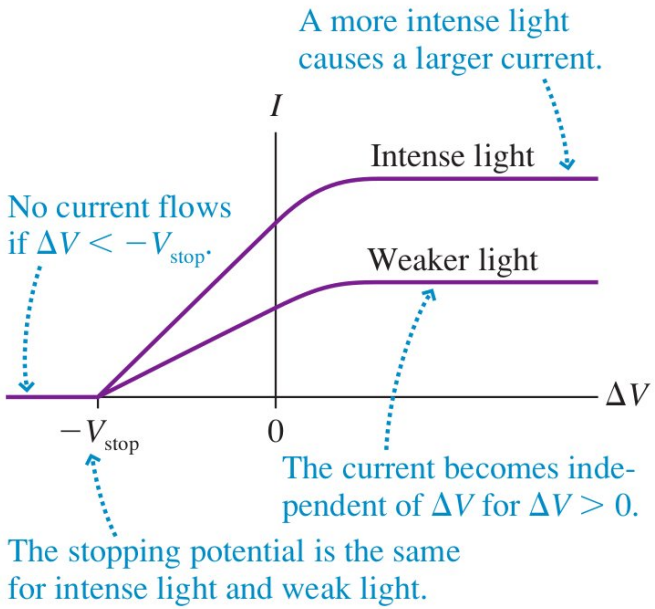
$\Delta V < 0$: A negative anode repels the electrons. Only the very fastest make it to the anode.

The *minimum* energy to remove a drop of water from the pool is *mgh*.



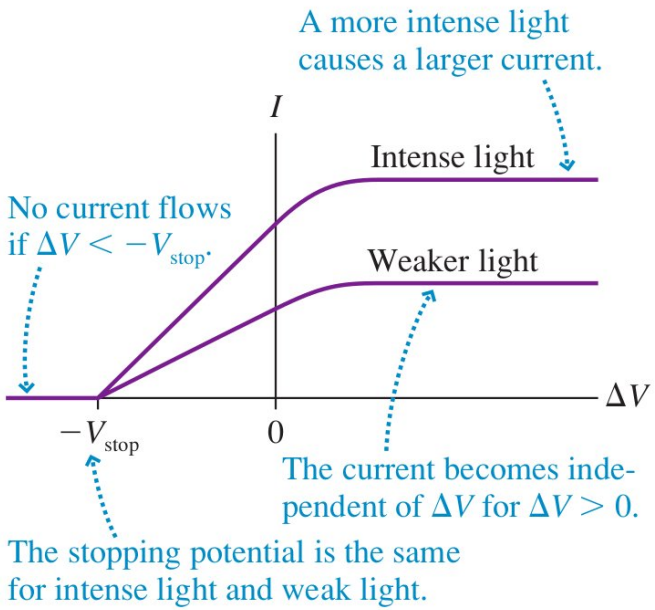
A helium laser pointer has a power $P = 1\ mW$ with a beam spot of radius $w = 1\ cm$. You shine the laser on a piece of tungsten which has atoms of radius $r = 1.41\ \text{Å}$ and work function $E_{ej} = 4.55\ eV$. Assume all of the light striking a single atom gets absorbed. What is the rate of electrons ejected from the surface? How long does it take for the first electron to get ejected?

1. Current directly proportional to intensity.

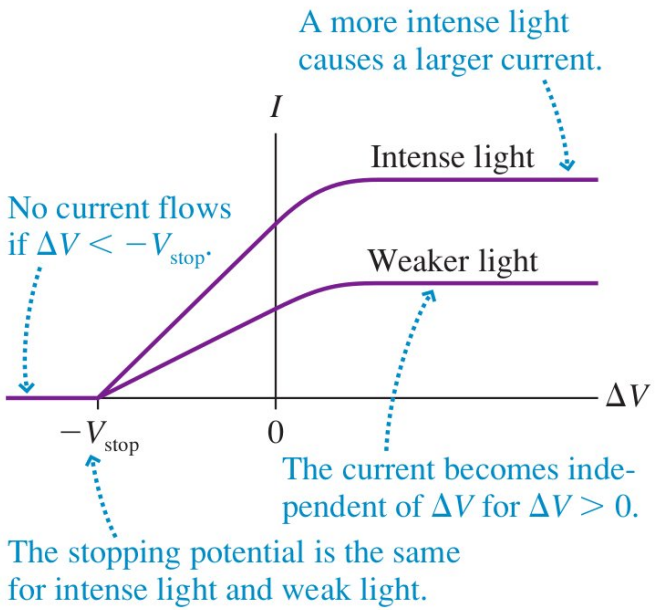


Photoelectric Effect Data - 1 36

1. Current directly proportional to intensity.
2. Current plateaus at positive ΔV.

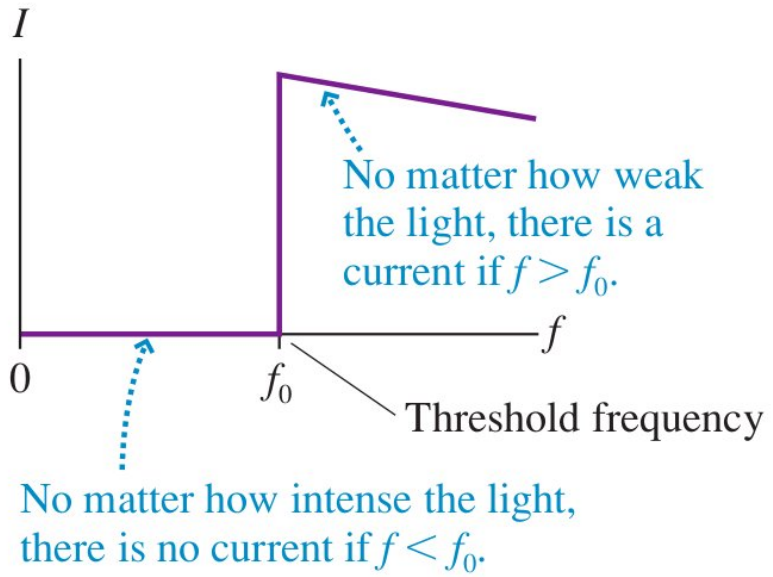


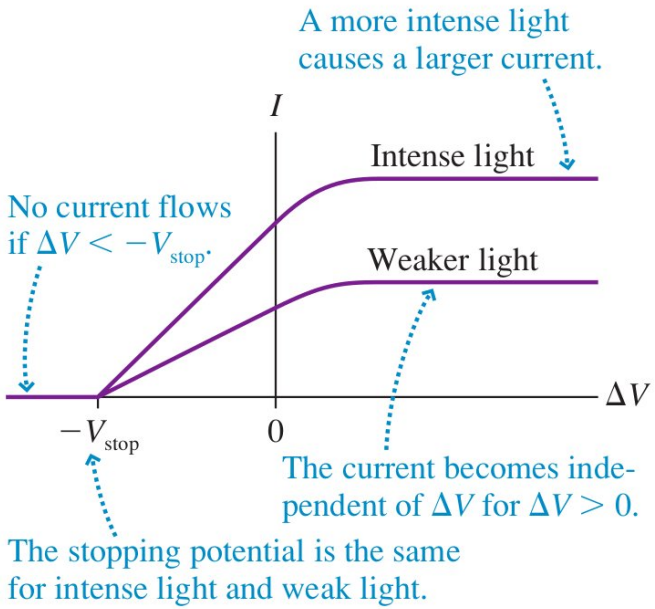
1. Current directly proportional to intensity.
2. Current plateaus at positive ΔV.
3. Current vanishes at V_{stop} regardless of intensity.



Photoelectric Effect Data - 1

1. Current directly proportional to intensity.
2. Current plateaus at positive ΔV.
3. Current vanishes at V_{stop} regardless of intensity.
4. The current appears without delay when the light is applied.





Photoelectric Effect Data - 1

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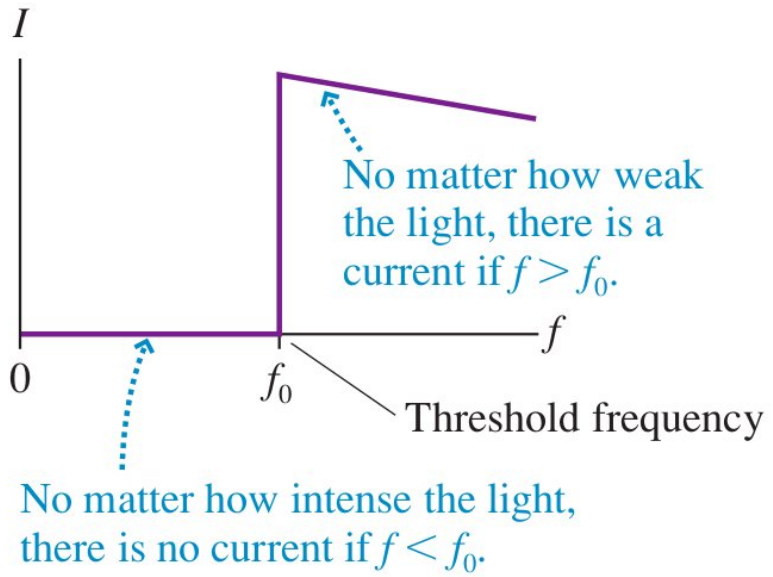
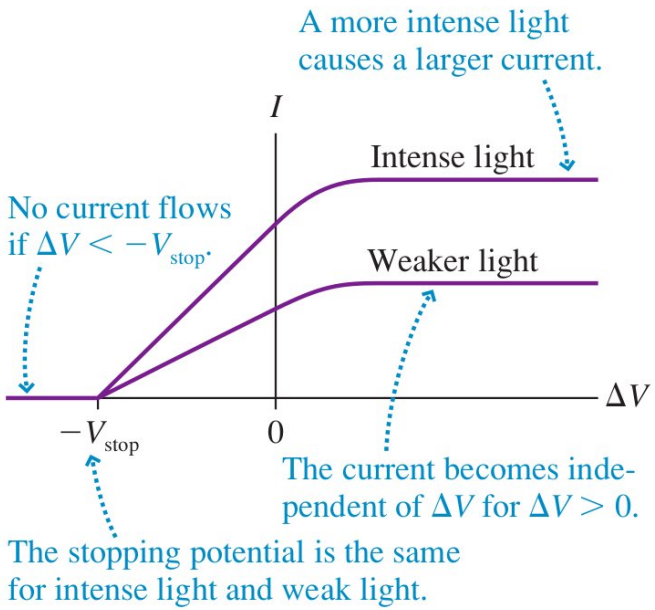
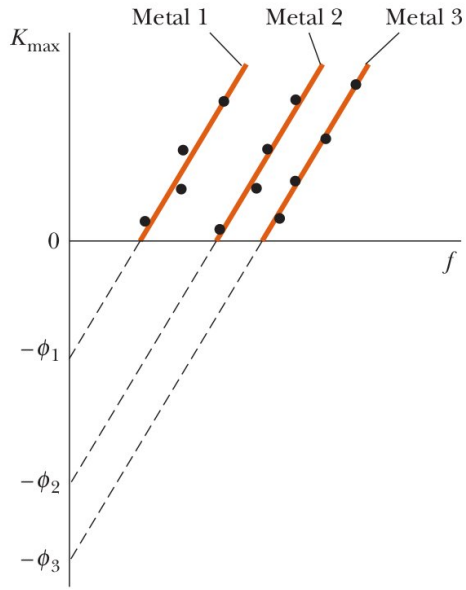
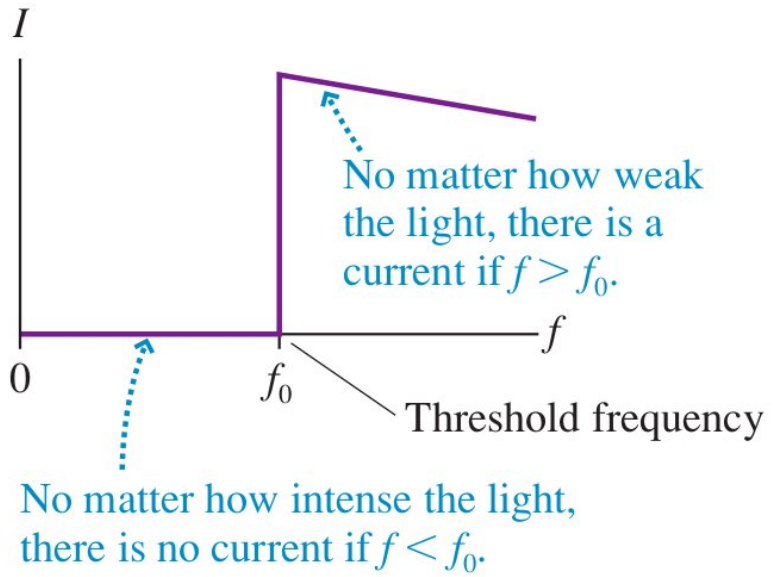
3. Current vanishes at V_{stop} regardless of intensity.
4. The current appears without delay when the light is applied.
5. Photoelectrons are emitted only if the light frequency f exceeds a threshold f_0.

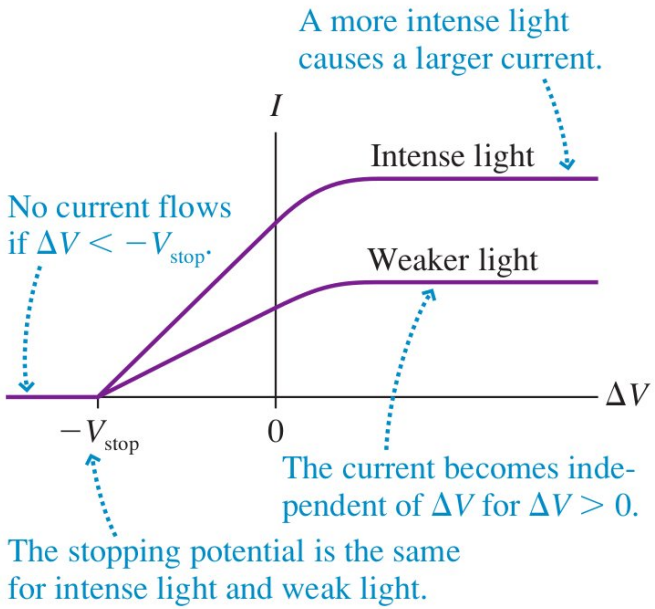


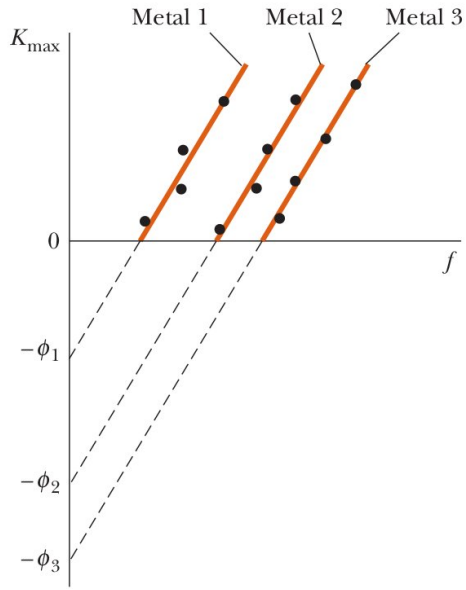




1. Current directly proportional to intensity.
2. Current plateaus at positive ΔV.
3. Current vanishes at V_{stop} regardless of intensity.
4. The current appears without delay when the light is applied.
5. Photoelectrons are emitted only if the light frequency f exceeds a threshold f_0.
6. Value of f_0 depends on the metal.



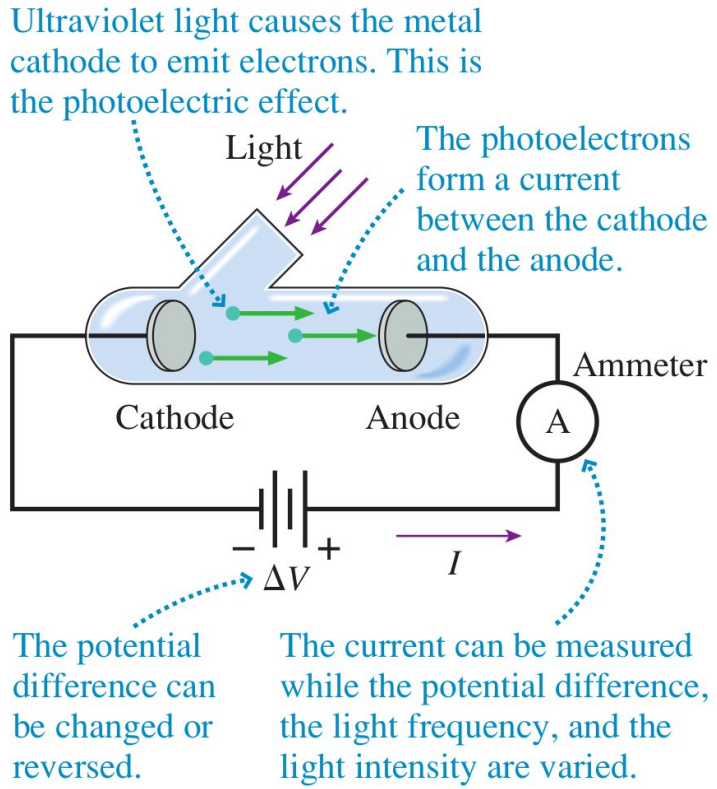


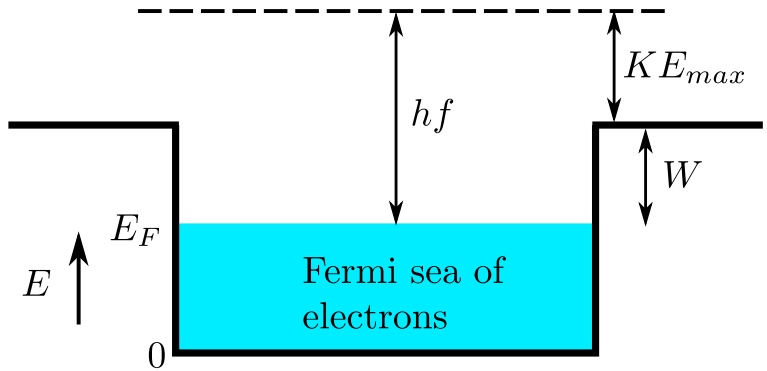


- By the late 19th century at least some of the properties of the photoelectric effect were known mostly due to the work of Philipp von Lenard (Nobel Prize, 1905).
- Max Planck (Nobel, 1918) had made the first use of the quantum hypothesis ($E = hf$)in explaining the blackbody radiation measurements (1900).
- The Young double-slit experiment and Maxwell's theory of electromagnetism had solidified the view of light as an electromagnetic wave instead of Newton's corpuscular theory.
- In 1905 along comes Einstein (Nobel Prize, 1921) and resurrects the corpuscular theory in the form of Planck's quanta

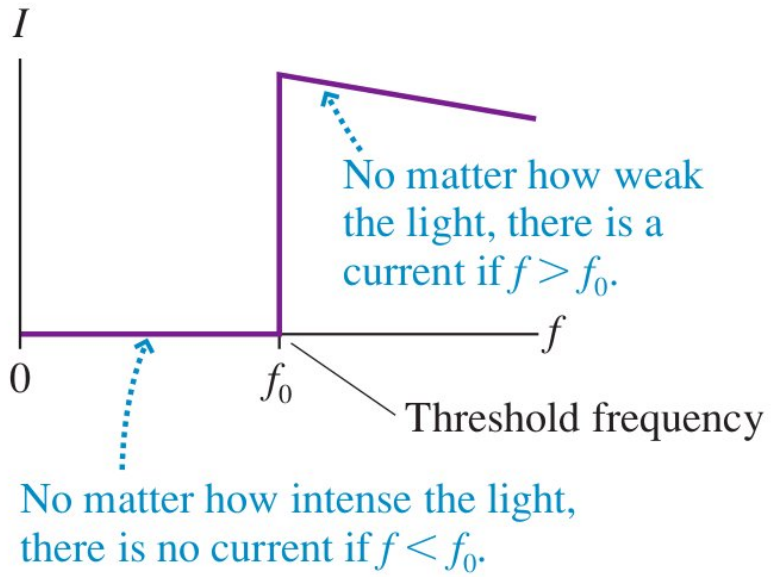
$$KE_{max} = hf - W$$

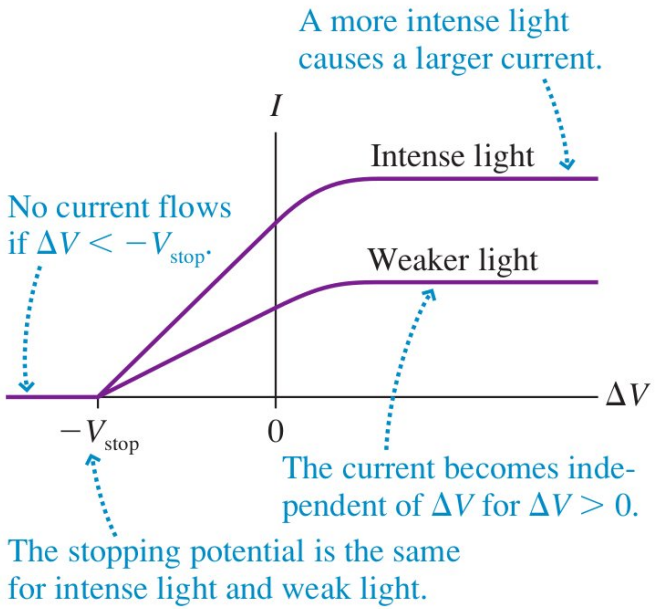
where $W = E_{ej}$ is the work function.

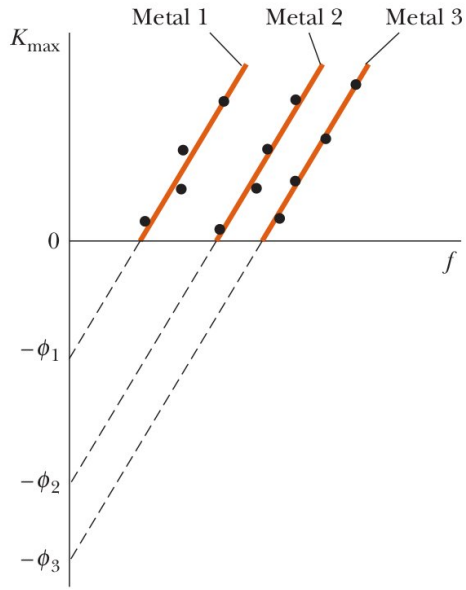




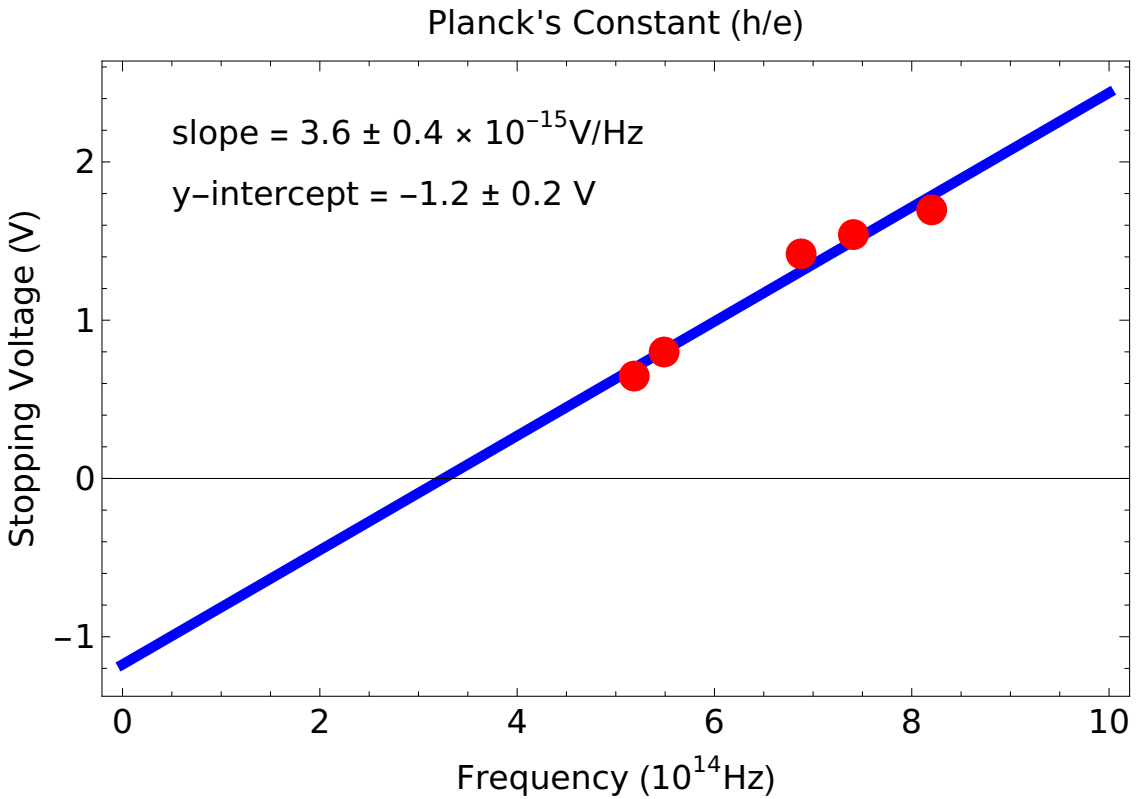
1. Current directly proportional to intensity.
2. Current plateaus at positive ΔV.
3. Current vanishes at V_{stop} regardless of intensity.
4. The current appears without delay when the light is applied.
5. Photoelectrons are emitted only if the light frequency f exceeds a threshold f_0.
6. Value of f_0 depends on the metal.







The plot below shows some results from Intermediate Lab on measuring Planck's constant and the work function of a metal. What is the relationship between the stopping voltage and the frequency f of the light striking the metal? What is the value of Planck's constant from the fit to the data?



Wave Particle Duality 44

Wave-particle duality is the concept in quantum mechanics that every quantum entity may be described as either a particle or a wave. It expresses the inability of the classical concepts ‘particle’ or ‘wave’ to fully describe the behaviour of quantum-scale objects. As Albert Einstein wrote:

“It seems as though we must use sometimes the one theory and sometimes the other, while at times we may use either. We are faced with a new kind of difficulty. We have two contradictory pictures of reality; separately neither of them fully explains the phenomena of light, but together they do.”

Wave Particle Duality 45

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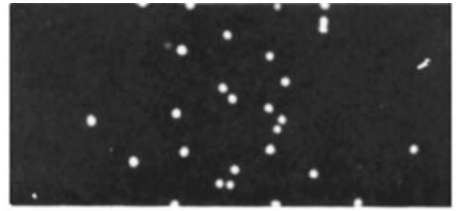
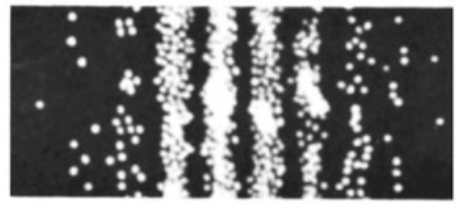
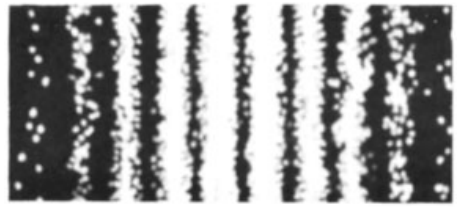


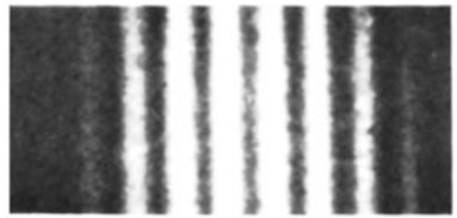
(a) After 28 electrons



(b) After 1000 electrons



(c) After 10000 electrons



(d) Two-slit electron pattern

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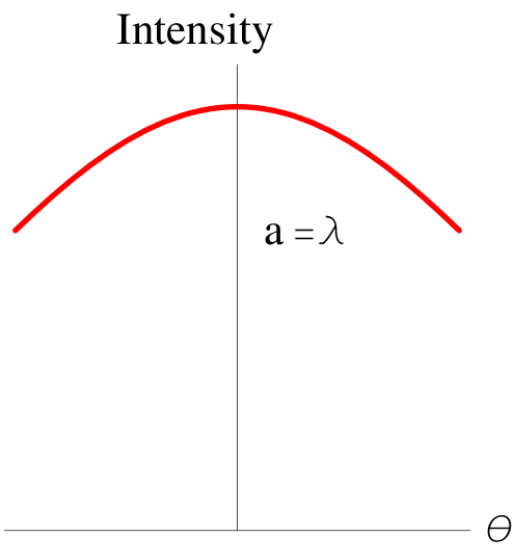
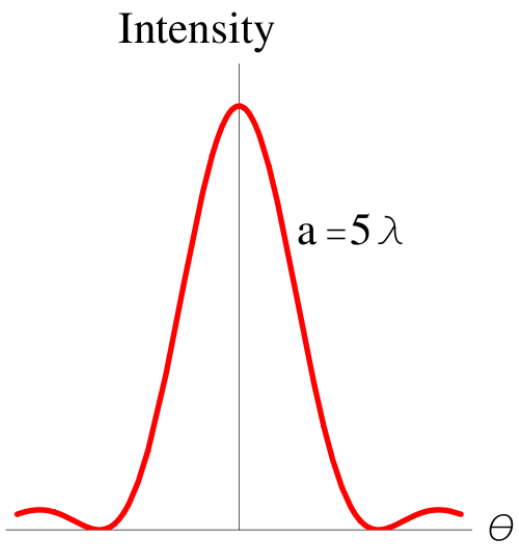
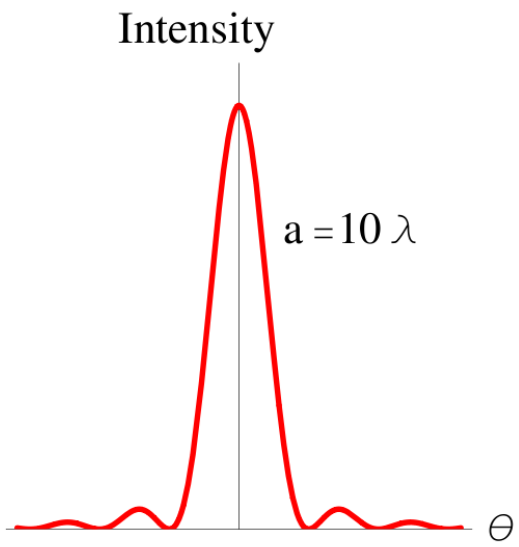
Diffraction Equation 46

$$I = I_m \left(\frac{\sin \alpha}{\alpha} \right)^2 = I_m \left(\frac{\sin \left(\frac{\pi a}{\lambda} \sin \theta \right)}{\frac{\pi a}{\lambda} \sin \theta} \right)^2$$

$$\alpha = \frac{\pi a}{\lambda} \sin \theta \qquad \theta \equiv \text{a} \textit{ngular position}$$







L'Hopital's Rule 47

If

$$f(a) = g(a) = 0$$

and

$$\lim_{x \to a^+} \frac{f'(x)}{g'(x)} = A$$

then

$$\lim_{x \to a^+} \frac{f(x)}{g(x)} = A$$