Monochromatic light wave with specific polarization

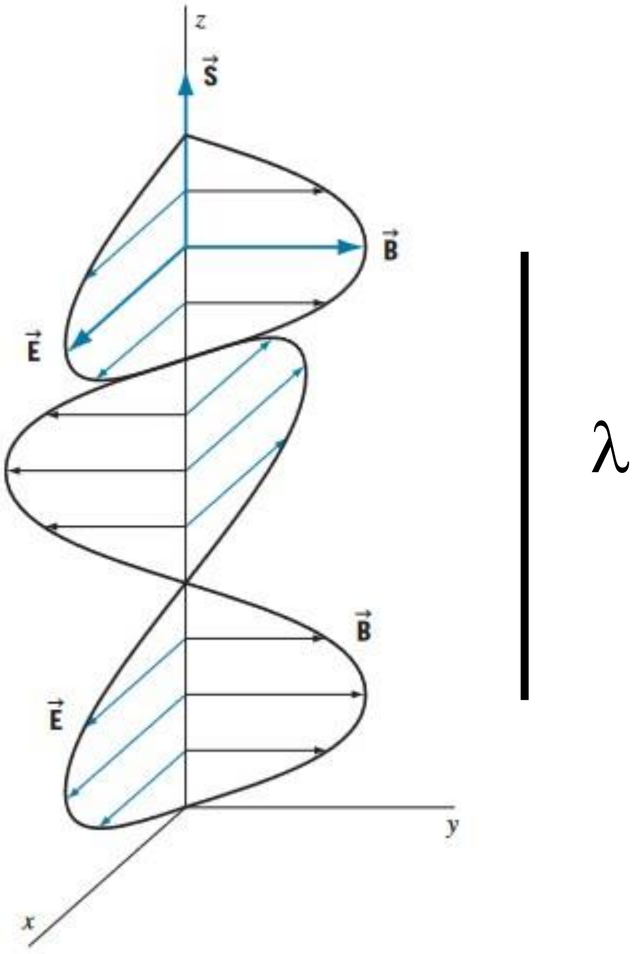
Travelling in +z direction

Polarization in x direction

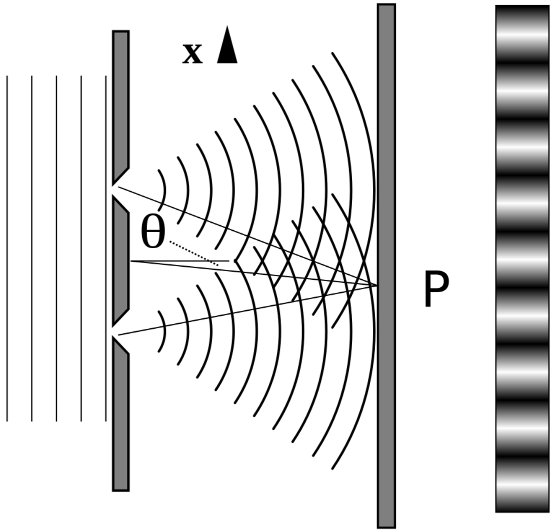
Cross product (right hand rule) connects the direction of E, B, travelling direction

What happens if you add two waves with same polarization?

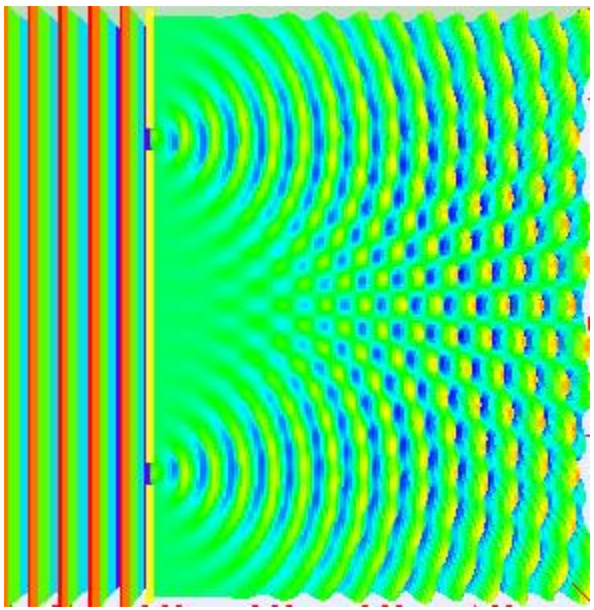
What happens if you add two waves with perpendicular polarization?



Two slit interference pattern (Wikipedia images)

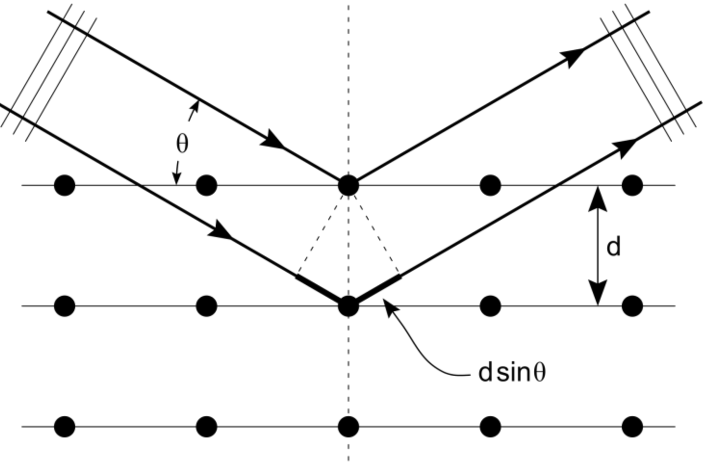


If the difference in path lengths is an integer number of λ, constructive interference (bright)

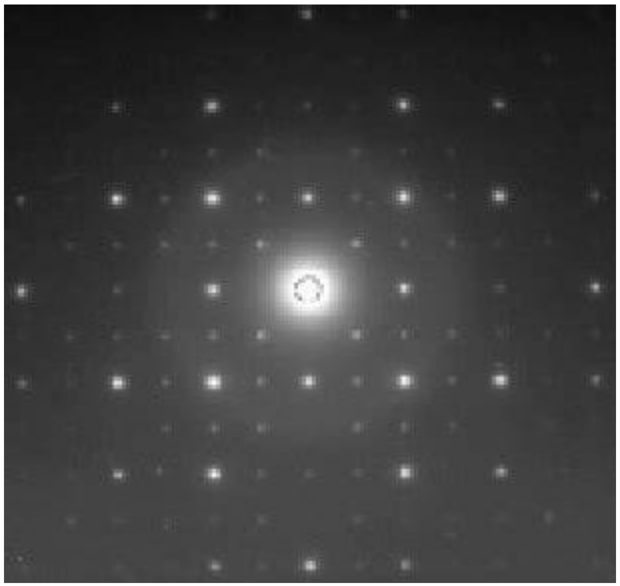


If the difference in path lengths is an half integer number (1/2, 3/2, 5/2…) of λ, destructive interference (dark)

X-ray diffraction pattern (Wikipedia images)

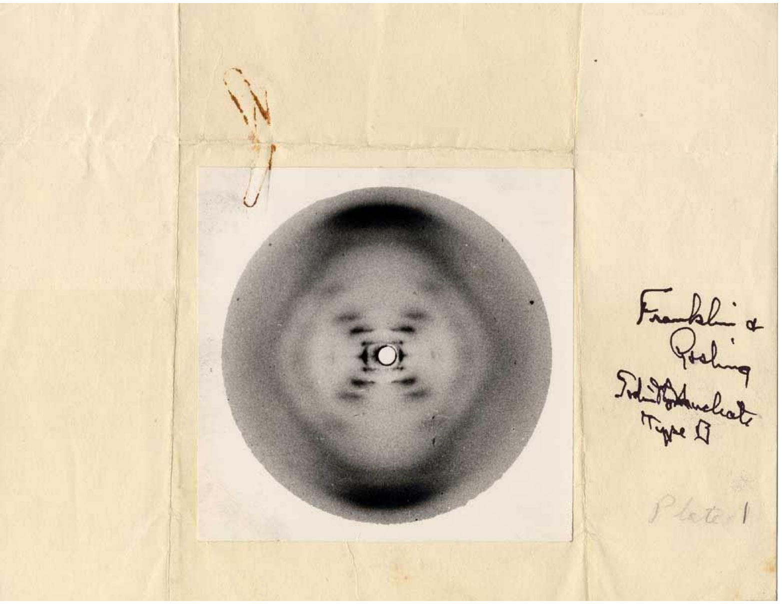


If the difference in path lengths is an integer number of λ, constructive interference (bright)

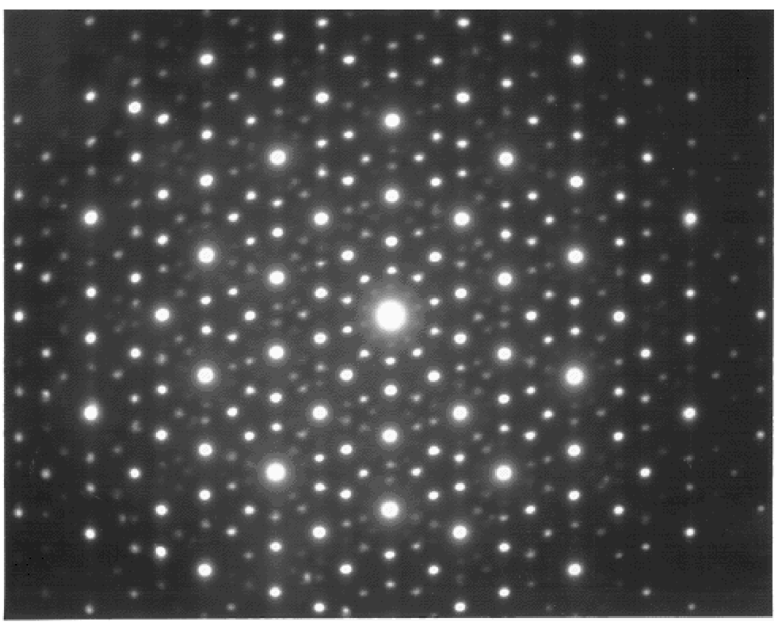


"Typical" diffraction pattern from cubic lattice because many ways to find planes

X-ray diffraction pattern: DNA & Quasi-crystal



Original X-ray diffraction pattern (Rosalind Franklin)



Wild result: Can’t tile space with 5-fold symmetry. Should never see 10-fold symmetry in X-rays!!

Question #1

You shine 1 mW of light with a wavelength of 450 nm on solid sodium. Electrons are ejected with an energy of 0.48 eV. If you increase the power of the light to 2 mW, then

(a) You measure that the rate for ejecting electrons is doubled but their energy remains the same.

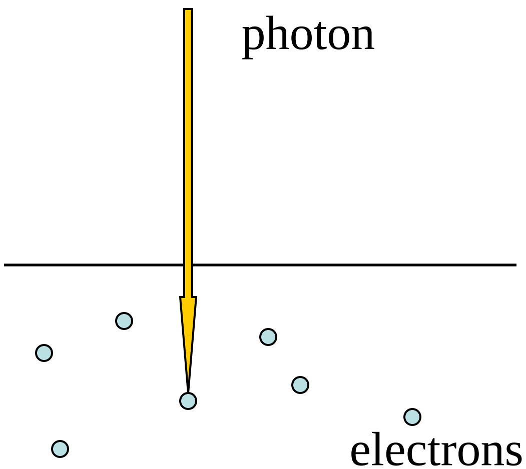
(b) You measure that the energy of each of the ejected electrons is doubled.

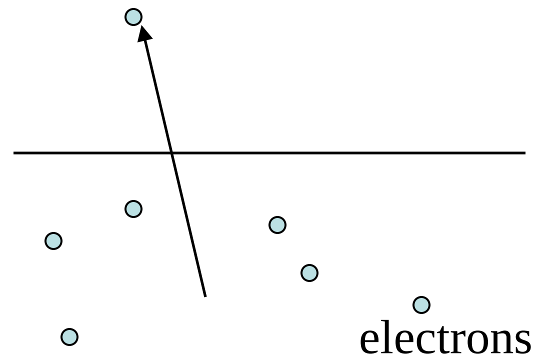
(c) You measure that the energy of the electrons increases by $h\, c / \lambda$

(d) You measure that both the number of electrons and their energy is doubled.

Conservation of Energy

What happens when an electron in a solid absorbs a photon?





Conservation of energy?

$E_{photon} + PE_{elec\ in} + KE_{elec\ in}$ before

$KE_{elec} + PE_{elec\ out} + E_{e\text{-}nuc} + E_{e\text{-}e}$ after

Why don't need to worry about conservation of momentum?

Photoelectric Effect

Book notation

$K_{max} = \frac{1}{2} m v^2_{max} = h f - \phi$

$K_{elec} = E_{photon} + PE_{elec\ in} + KE_{elec\ in} - (PE_{elec\ out} + E_{e\text{-}nuc} + E_{e\text{-}e})$

What (physically) is ϕ?

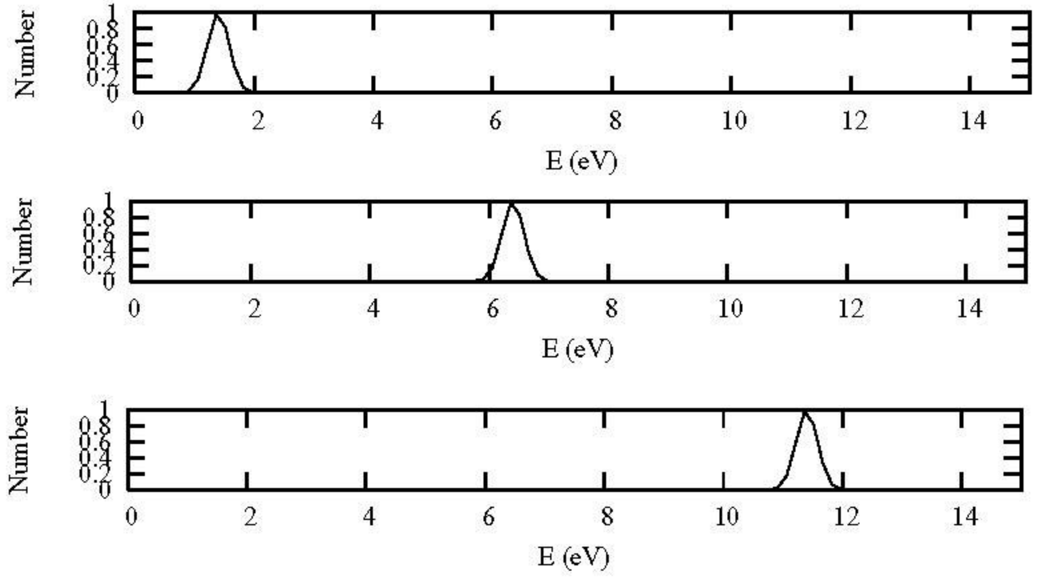
Why max in subscript?

ϕ is called the work function; units of energy; typically given in eV (1 eV = charge of 1 electron X 1 Volt is roughly 1.60 X 10^{-19} J). Typical value of work function is < 7 eV. Why is ϕ positive?

Why can't 1 electron absorb 2 photons?

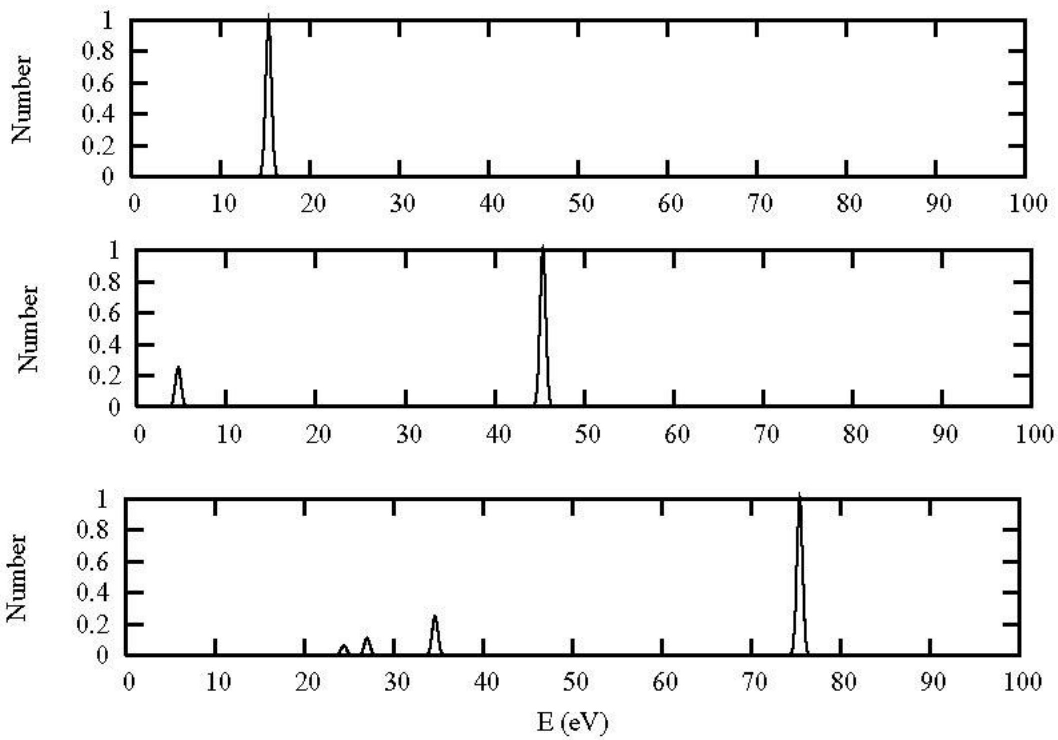
Problem

When a hydrogen atom absorbs a photon with energy of (a) 15 eV, (b) 20 eV, and (c) 25 eV, the measurements of the energy of the outgoing electron looks like the curves below. How much energy is needed to ionize a hydrogen atom? What wavelength is this? Where is this in the spectrum (infrared, visible, UV, …)?



Problem

When a helium atom absorbs a photon with energy of (a) 40 eV, (b) 70 eV, and (c) 100 eV, measurements of the energy of the outgoing electron looks like the curves below. How much energy is needed to ionize a helium atom? What is the physical reason for the other peaks in the graph? Why no extra peaks in H?



Question #2

Which statement is most correct about light & material that are in thermal equilibrium?

(a) A good absorber of light is a good emitter.

(b) A good reflector of light is a good emitter.

(c) More light energy can be absorbed than emitted.

(d) More light can be emitted than absorbed.

(e) It is impossible to make a connection between absorption and emission of light.

Question #3

A perfectly black sphere with a radius of 1 m radiates 5 W and temperature T (in K). A perfectly black sphere with a radius of 2 m at the same temperature radiates

(a) 5 W

(b) 10 W

(c) 20 W

(d) 5/2 W

(e) 5/4 W

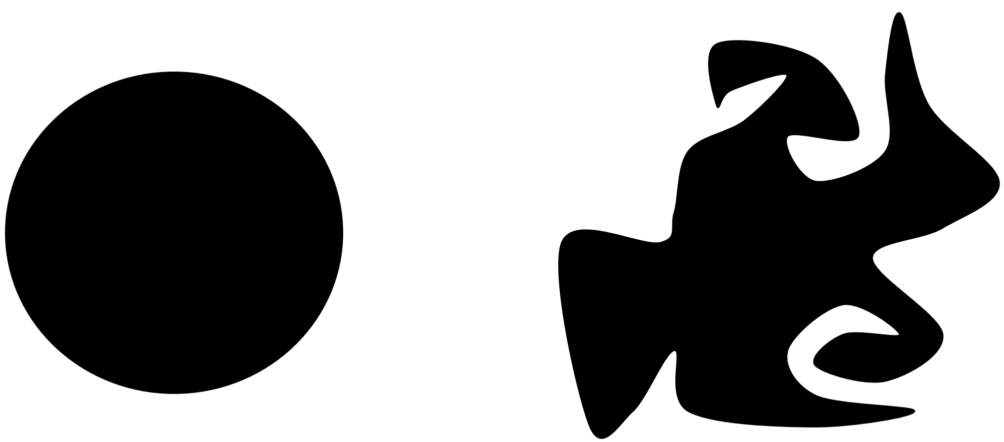
Black Body

An ideal black body absorbs **all** electro-magnetic radiation that hits it (cavity w/ small hole). The power radiated per unit area of a black body is given by (Stefan)

$R = \sigma T^4$

$\sigma = 5.6703 \times 10^{-8}$ W/(m^2 K^4)   Note units!

Does this have the correct trends? Does this formula hold for all shapes? Can estimate T of earth from this!!!!



Planck's Kluge

A harmonic oscillator is not allowed to have any possible energy.

The only allowed energies are given by

$E_n = n\,\varepsilon = n\,h\,f$

$f = \omega/2\pi$ is the frequency of the oscillator

$h = 6.626 \times 10^{-34}$ J s is known as Planck's constant

$P_n = N \exp(-E_n/k_B T)$ is the probability to have energy E_n

$$\overline{E} = \sum_{0}^{\infty} E_n \exp(-E_n/k_B T) \Big/ \sum_{0}^{\infty} \exp(-E_n/k_B T)$$

$$\overline{E} = h f/[\exp(h f/k_B T) - 1]$$

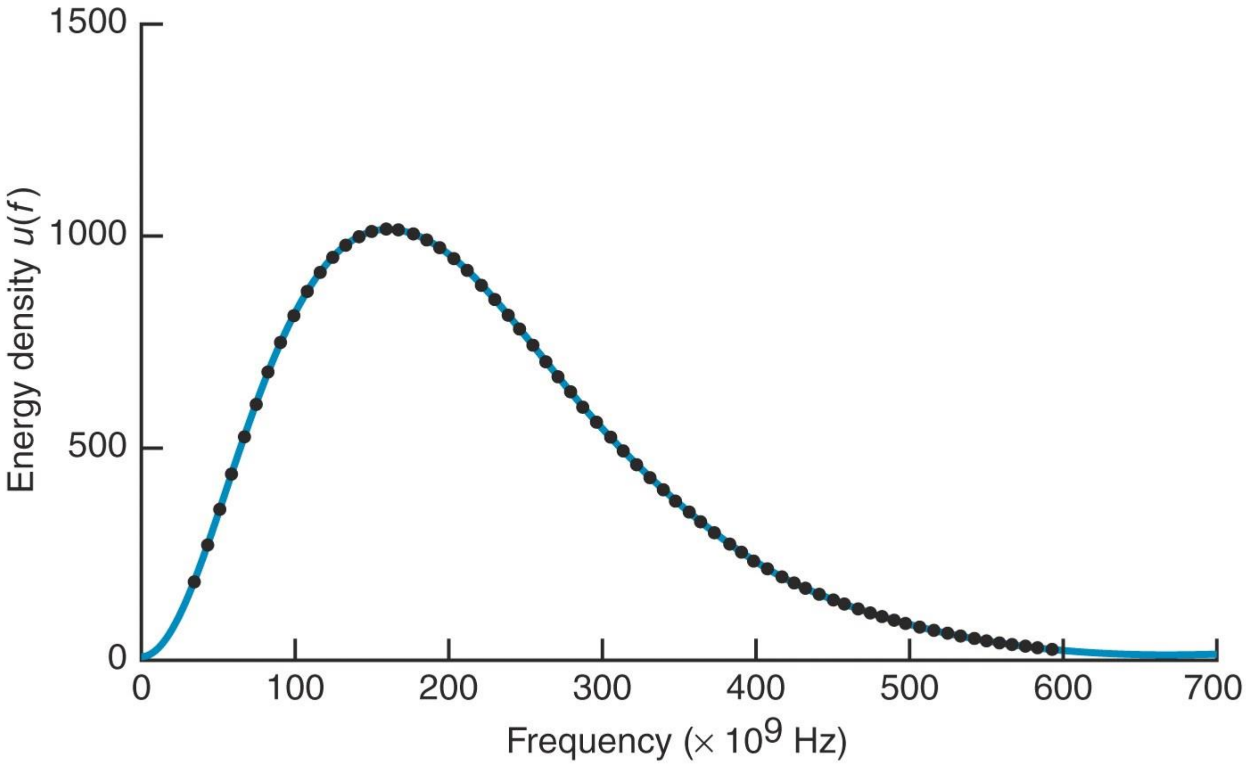
Summation Trick

$(1 - x)(1 + x + x^2 + \ldots x^m) = 1 - x^{m+1}$

$1 + x + x^2 + \ldots = 1/(1 - x)$ if $x < 1$

$0 + x + 2x^2 + 3x^3 + \ldots = x(d/dx)(1 - x)^{-1} = x/(1 - x)^2$

Cosmic Background



From COBE, blue line Planck's law with T = 2.735 K and dots are measurements of the radiation in space. Partial evidence for the Big Bang. Is classical result at larger or small f?

Question #4

When a photon scatters from an initially stationary electron, the

(a) photon wavelength increases and the electron energy increases.

(b) photon wavelength decreases and the electron energy increases.

(c) photon wavelength increases and the electron energy decreases

(d) photon wavelength decreases and the electron energy decreases

Scattering of Photon

Not only are photons absorbed & emitted by atoms, they can be scattered by objects. Because photons have such small momentum compared to their energy, the object they scatter from hardly recoils unless very light. The biggest effect is when the mass of the object is smallest. Why scatter photon off of electron? Why scatter X-rays instead of visible light?

Conservation Laws

Energy: $E_{p,1} + E_{e,1} = E_{p,2} + E_{e,2}$

x-momentum: $E_{p,1}/c = (E_{p,2}/c)\cos\theta + P_{e,2}\cos\phi$

y-momentum: $0 = (E_{p,2}/c)\sin\theta - P_{e,2}\sin\phi$

E/momentum: $(c\,P_{e,2})^2 = (E^2_{e,2} - E^2_{e,1})$

$E_{e,1} = M_e\,c^2 = m\,c^2$

E/wavelength $E_p = h\,c / \lambda$

Can solve for final wavelength in terms of initial wavelength and the direction that the photon scatters

Must use relativistic expression for E!

Compton Scattering

$$\lambda_2 = \lambda_1 + (h / m c)(1 - \cos\theta)$$

Does this equation make sense? Are units correct?

$h / m c = 2.426 \times 10^{-12}$ m

Should the photon wavelength get longer after scattering?

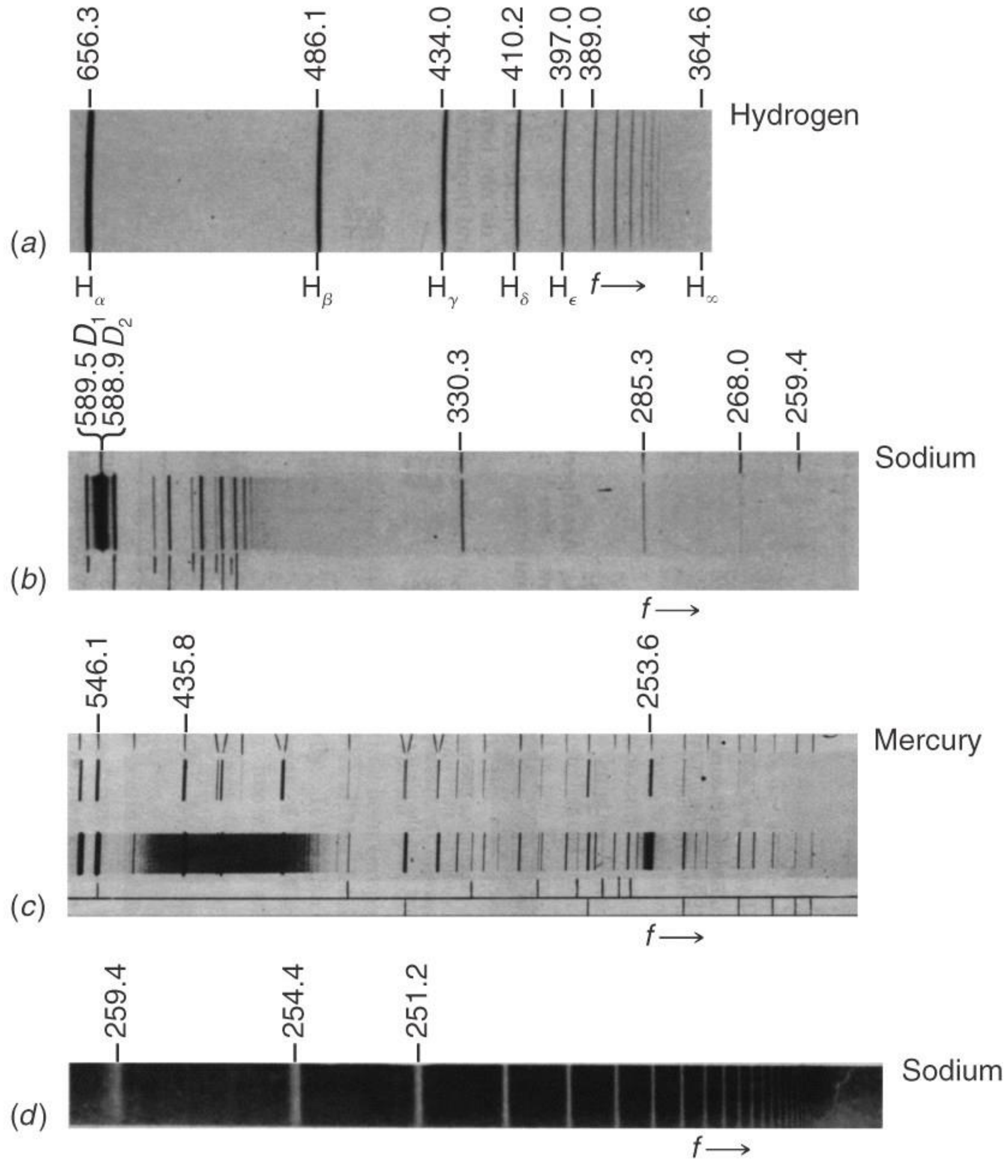
Should the effect be smaller/larger as the mass gets larger?

Should the effect be smaller/larger as the scattering angle gets larger?

Should there be change in wavelength for no scattering? What angle is this?

How can we get electron information?

Atomic Spectra



Atoms only emit and absorb light near specific λ for longer wavelengths

Each atom has its own "fingerprint"

How we know the composition of stars.

How we know speed of stars/galaxies/…

Atomic Spectra

48 PHOTOIONIZATION OF THE SCANDIUM ATOM. I. . . . 4435

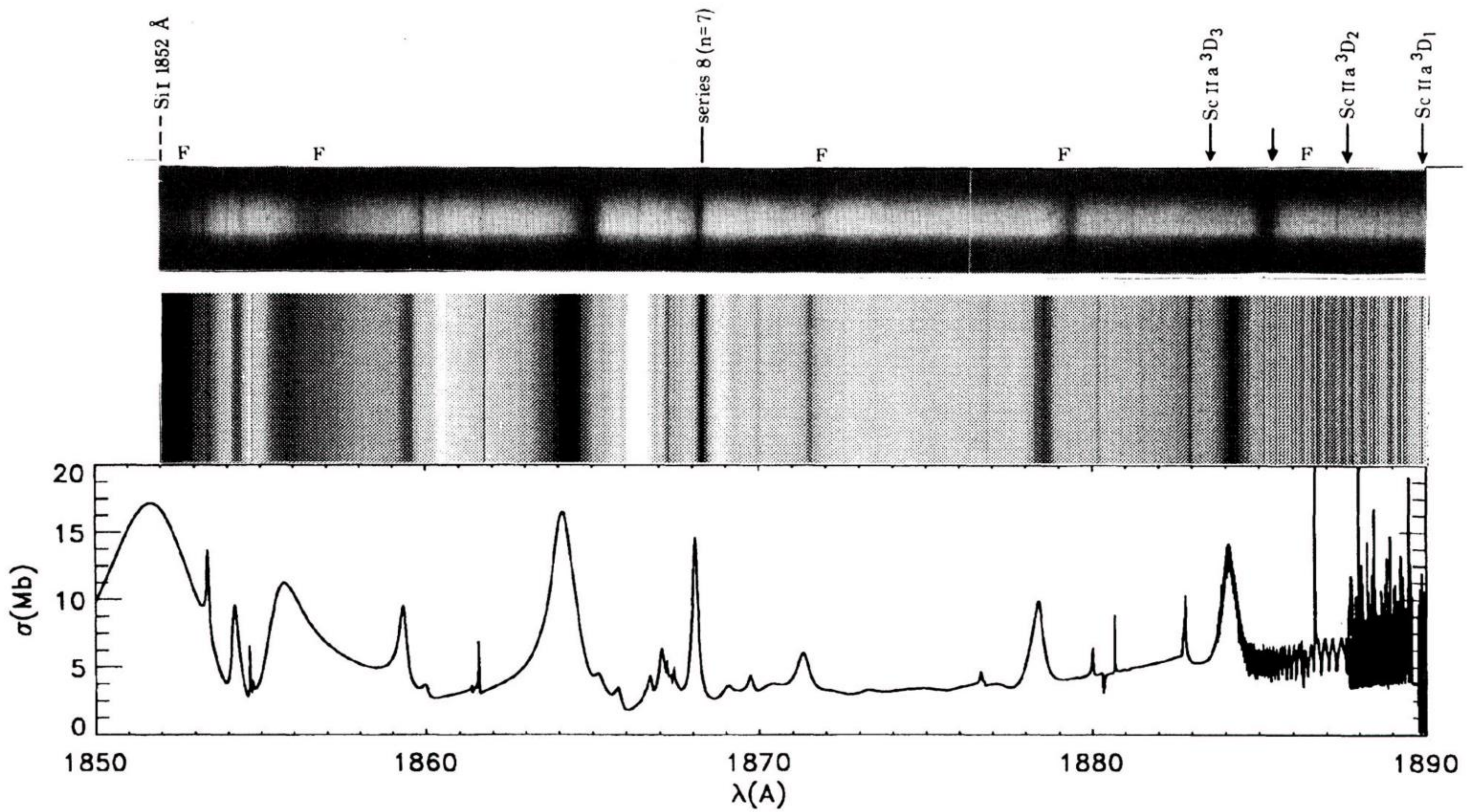
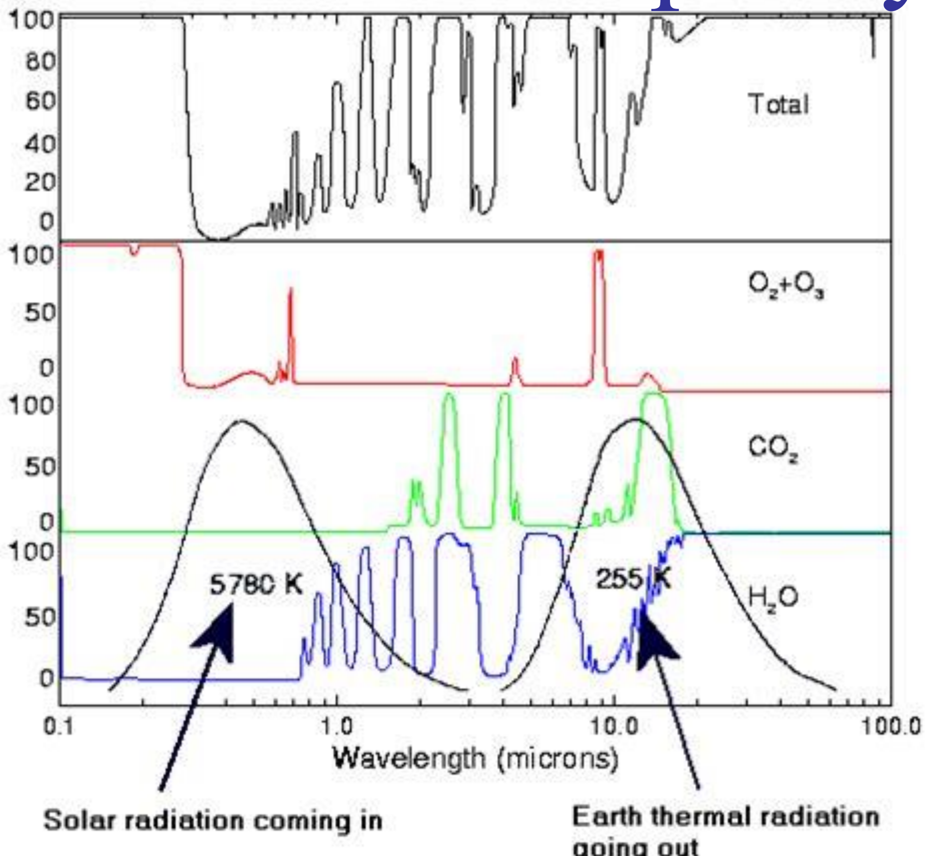


FIG. 5. Photograph (top) of one of the plates of Garton *et al.* [5] with a simulation (middle) of a plate using the theoretical cross section. Below these is the Sc photoionization cross section in the length gauge.

At shorter wavelengths the absorption spectra has peaks but doesn't go to ~0 in between because of photoelectric effect (electron leaves)

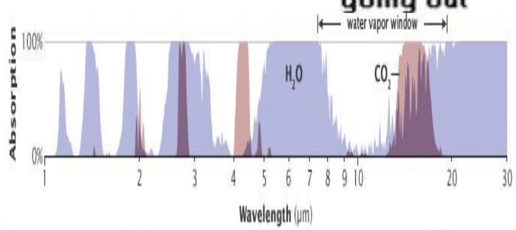
Relevant opacity of atmosphere

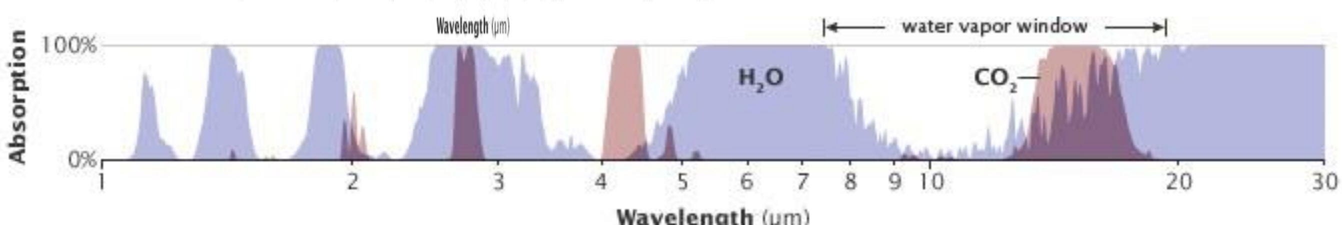


Why is small amount of CO_2 important?

The atmosphere hardly absorbs light from the sun

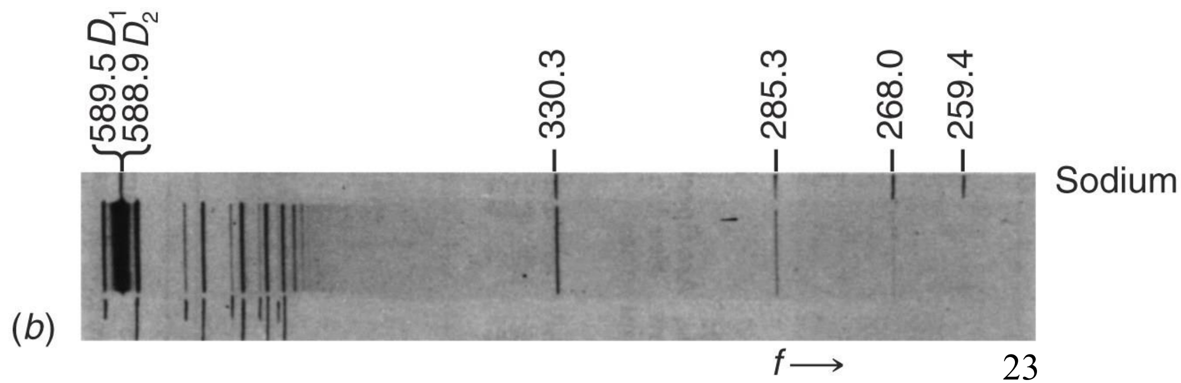
The thermal light from earth overlaps the water window and can mostly get out. CO_2 adds to the the absorption in the water window.





Specific Example

Light with a wavelength of 590 nm is being used to slow an atom of sodium, Na. The sodium atom has a mass of 3.82 X 10^{-26} kg and a speed of 200 m/s. (a) What is the KE of the Na atom in J and in K? (b) What is the energy of the photon? (c) What is the momentum of the photon? (d) What is the average change in velocity of the Na atom after absorbing/emitting 1 photon? (e) On average how many photons must be absorbed to slow the Na by 1 m/s? (f) What is the recoil limit of the cooling?



Answer

(a) $KE = \frac{1}{2} m v^2 = 7.64 \times 10^{-22}$ J $= k_B$ 55.4 K

(b) $E_{phot} = h c / \lambda = 3.37 \times 10^{-19}$ J (much larger than KE)

(c) $p_{phot} = E_{phot} / c = 1.12 \times 10^{-27}$ kg m/s

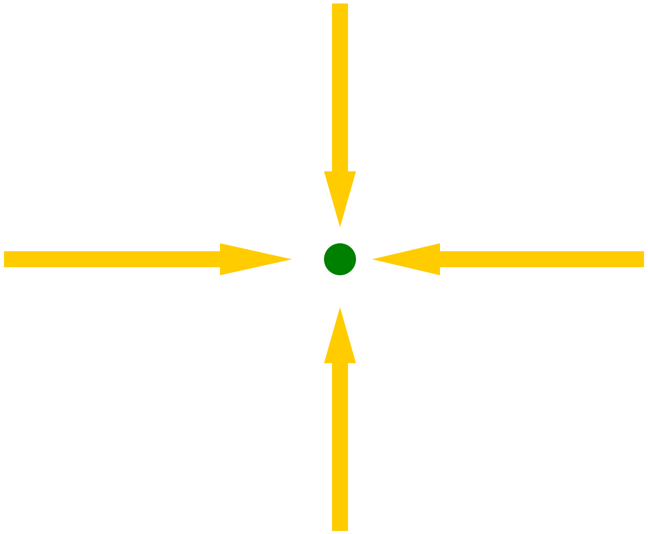
(d) $\Delta v_{av} = p_{phot} / m_{Na} = 0.029$ m/s

(e) $N = 1$ m/s $/ \Delta v_{av} = 34$

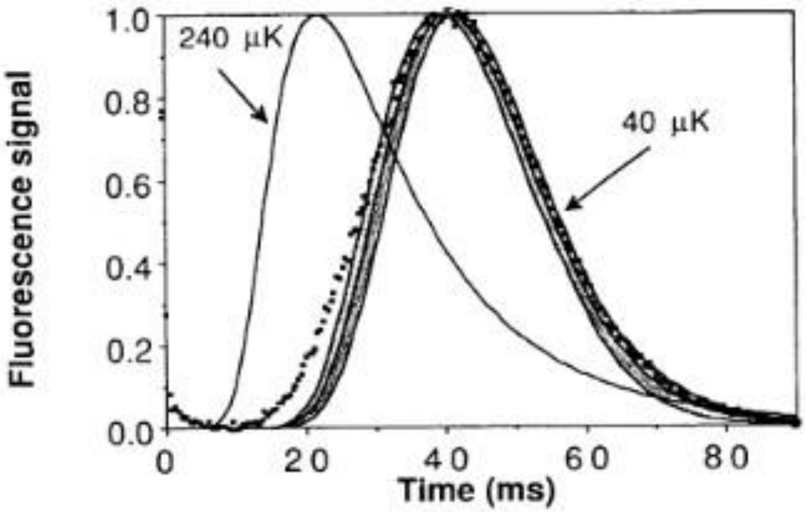
(f) $E_{rec} = \frac{1}{2} m \Delta v^2 = 1.65 \times 10^{-29}$ J $= k_B\ 1.2 \times 10^{-6}$ K … So the laser cooling limit is roughly 1.2 μK but other processes usually lead to much higher limit for T

Laser Cooling of Gases

Atomic vapors are routinely cooled to roughly 10 μK using lasers. By properly tuning the laser frequency, atoms are more likely to absorb light from the beam they are moving toward: optical molasses. After absorbing a photon, the atom re-emits it in a random direction. Explain why laser cooling works? Why is there a “recoil limit” to the cooling?



Laser Cooling of Atoms



Paul D. Lett, et al, Phys, Rev. Lett. 61, 169 (1988). https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.61.169

Used the time of arrival to figure out the atoms' speed and temperature

We have measured the temperature of a gas of sodium atoms released from "optical molasses" to be as low as 43 ± 20 μK. Surprisingly, this strongly violates the generally accepted theory of Doppler cooling which predicts a limit of 240 μK. To determine the temperature we used several complementary measurements of the ballistic motion of atoms released from the molasses.

At end of paper, they say 2 other groups found similar effect

Other methods lead to even lower temperatures. I think the current record is 38 picoK (10^{-12} K) C. Deppner et al, Phys. Rev. Lett. 127, 100401 (2021). Description for "general science audience" at https://physics.aps.org/articles/v14/119

Is light particles or waves?

Neither!!!

Good arguments that light is composed of particles that, in some circumstances, have wave characteristics.

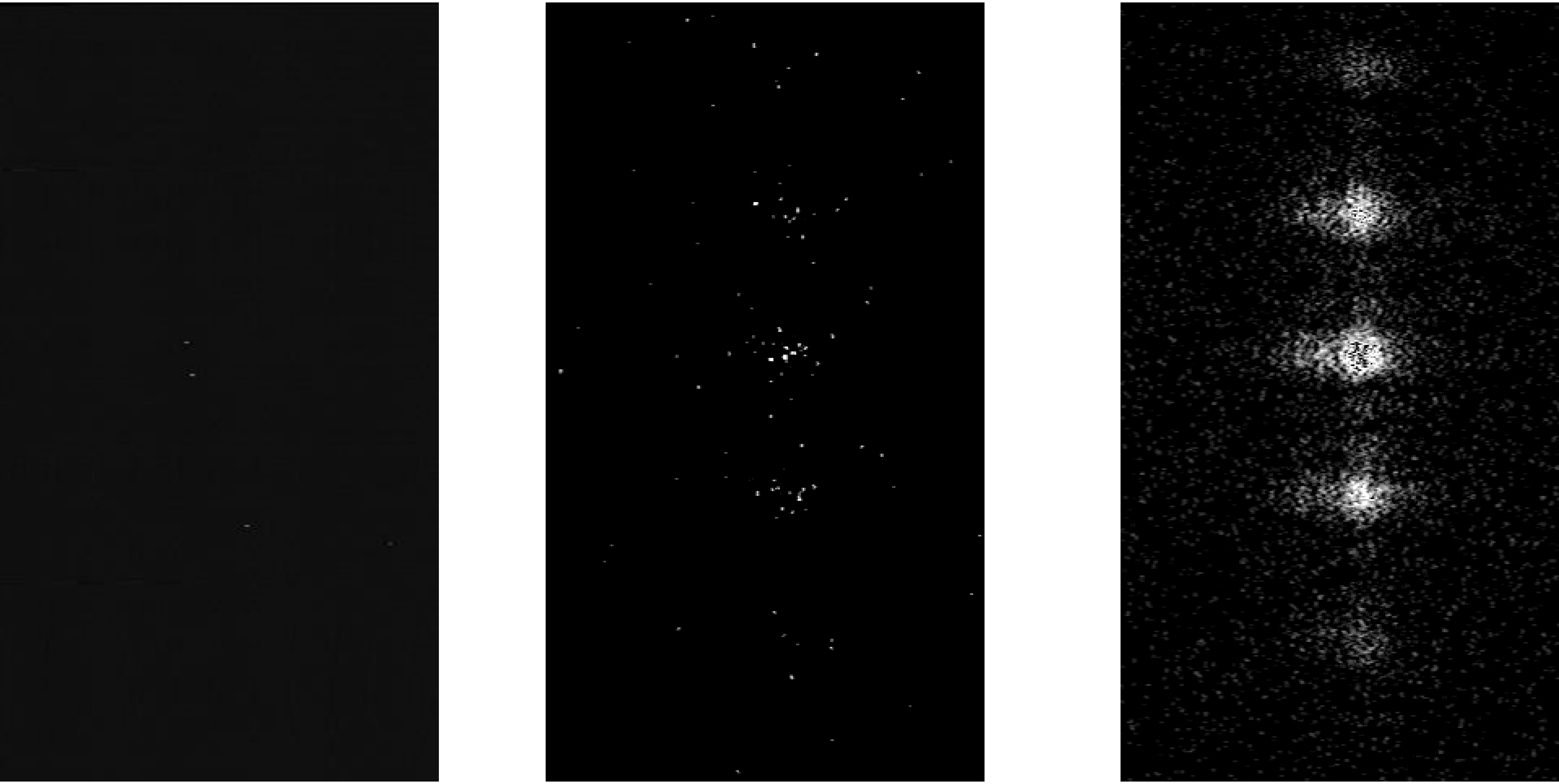
Good arguments that light is a wave that, in some circumstances, has particle characteristics.

No experimental evidence to decide.

I favor the latter way of thinking. This class won't dwell on this controversy. We will focus on outcomes.

How two slit interference works

Experiment by Robert Austin & Lyman Page (Princeton Univ)

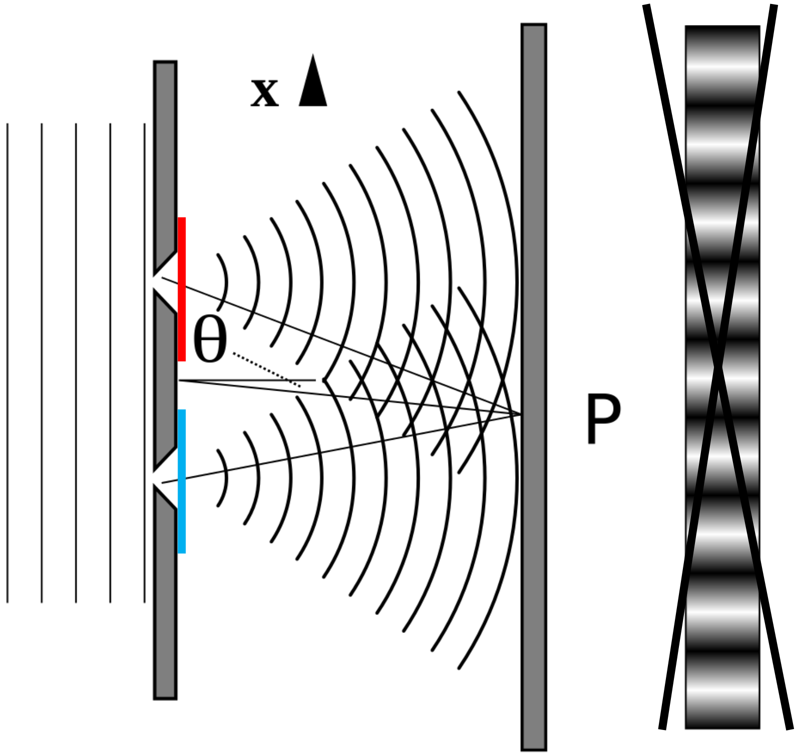


1/30 sec (5 photons) 1 sec 100 sec

Each individual photon interferes with itself!?

Detect which slit

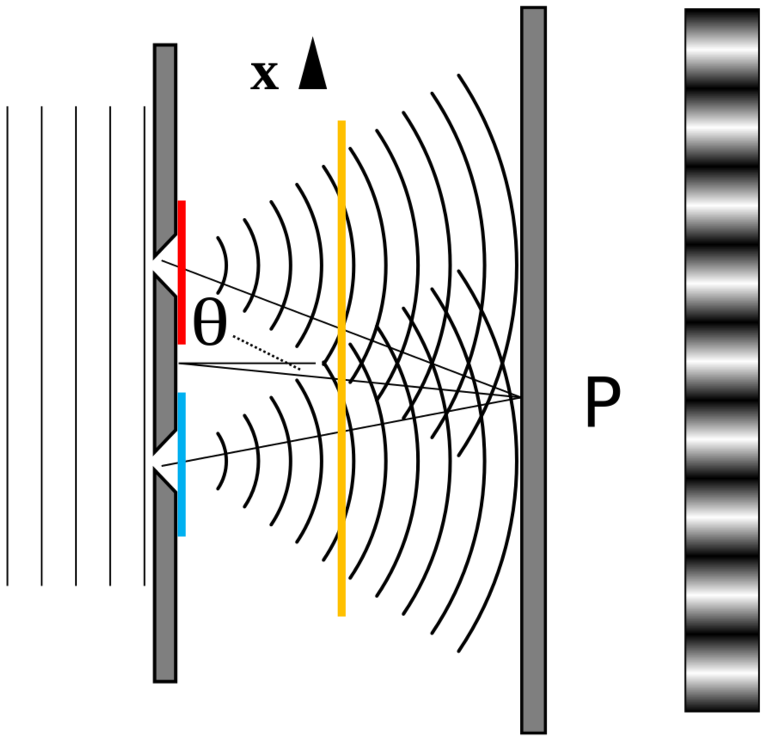
Put a polarizer behind each slit (one along page and one perpendicular to page)
Can now tell which slit each photon goes through



No interference pattern even if don't detect the polarization of the photon

Restore interference!

Put a polarizer behind each slit (one along page and one perpendicular to page)
Put a 3rd polarizer between at 45 deg to both polarizers



Interference pattern returns because can no longer tell which slit photon went through (Quantum eraser)

Different angles give mixture of interference and no interference

"Delayed-choice gedanken experiments and their realizations" X. Ma, J. Kofler, and A. Zeilenger, Rev. Mod. Phys. 88, 015005 (2016).
https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.88.015005