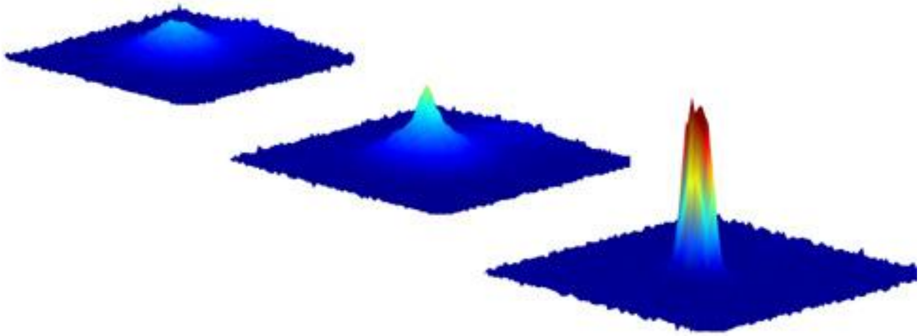
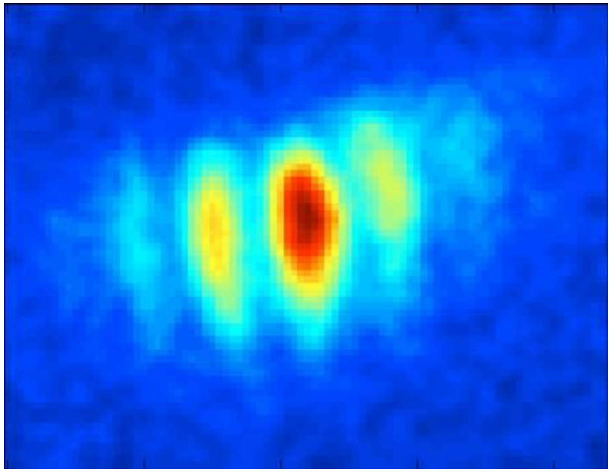
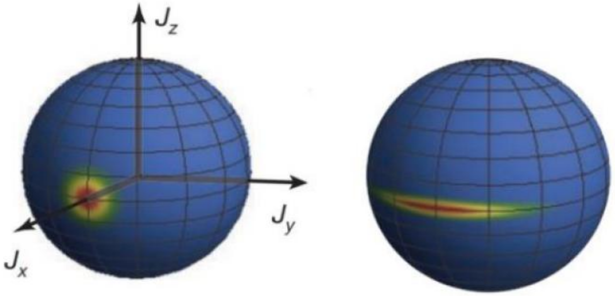




Physics 430 and Physics 631

Quantum Optics & Atomics



[Kasevich group, Stanford U.]

Instructor

Prof. Seth Aubin

Office: room 255, Small Hall, tel: 1-3545

Lab: room 069, Small Hall, tel: 1-3532

e-mail: saaubi@wm.edu

web: http://www.physics.wm.edu/~saubin/index.html

Office hours: Wednesdays 4-5 pm

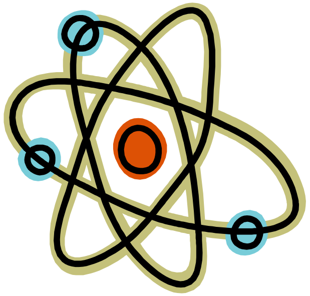
Mohsin Jamil

Office: rooms 023 and 024, Small Hall
e-mail: mjamil@wm.edu

Office hours: Thursdays 4-5 pm

Course Objectives (I)

Introduce the ***basic physics***, **theory**, **current research topics**, and **applications** of ***Atomic Physics and Quantum Optics***.



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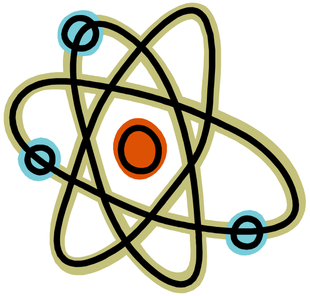

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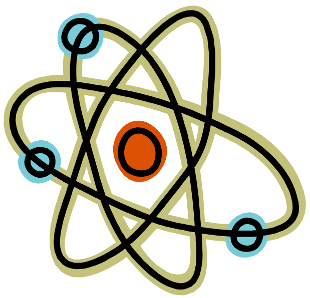

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- **Angular momentum** of light and atoms.
- **Multi-level** quantum systems.
- **Laser cooling and trapping**.
- Quantum theory of light, **dressed atoms**, squeezing.
- **Quantum gases:** Bose-Einstein condensation, atom-atom interactions.
- **Spin squeezing,** entanglement … quantum Fourier transform (Shor's alg.)

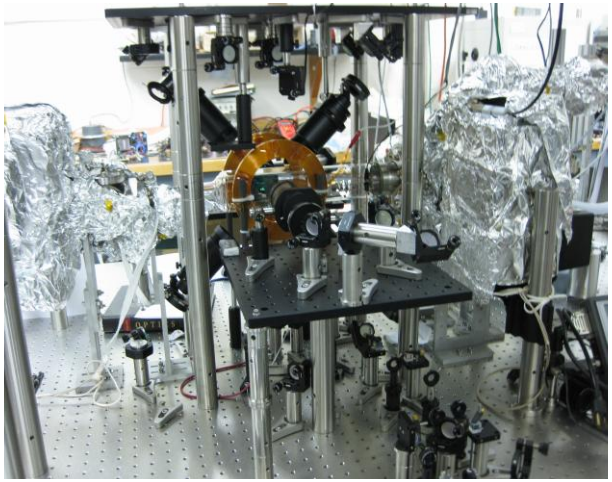
Course Objectives (II)

Experimental Demonstrations

Seeing is believing … Demonstration topics:

- **Research lab visits.**
- **laser cooling and trapping**.
- **Magnetic trapping.**
- **Saturation spectroscopy.**
- **Spatial and temporal coherence.**
- **Particle behavior of light.**

etc ...



Scientific Articles and Presentations

Practice reading and writing scientific articles and making science presentation.

Course Work

- **Problem sets:** not-quite weekly, extra problems for graduate students.
- **Participation:** class attendance, classroom discussion.
- **Midterm** (before spring break).
- **Undergraduate students** (work done in teams of two):
  - **Final paper** (4 pages, single space, *Phys. Rev. Lett.* format).
  - **Oral presentation** on the same subject matter.
- **Graduate students:** **Final exam** (December 11, 9 am - noon)

Undergraduate Grading

Problem sets	30 %
Participation	10 %
Midterm	25 %
Final paper	20 %
Oral presentation	15 %
Total	**100 %**

Graduate Grading

Problem sets	35 %
Participation	10 %
Midterm	25 %
Final Exam	30 %
Total	**100 %**

References

The course materials will be taken from original physics papers and the following texts:

Laser Cooling and Trapping, Metcalf and van der Straten.

Quantum Theory of Light, Loudon.

Cold Atoms and Molecules, Weidemüller and Zimmermann.

Introduction to Quantum Optics, Grynberg, Aspect, and Fabre.

Optical Coherence and Quantum Optics, Mandel and Wolf.

Atomic Physics, Foot.

Bose-Einstein Condensation in Dilute Gases, Pethick and Smith.

Quantum Mechanics, Cohen-Tannoudji, Diu, Laloë.

Quantum and Atom Optics, by D. Steck
https://atomoptics.uoregon.edu/~dsteck/teaching/quantum-optics/quantum-optics-notes.pdf

Schedule (I)

Week 0: 8/28 **Intro to Atomic Physics and Quantum Optics**
Introduction to atom-light interactions, semi-classical atomic physics.

Week 1: 9/2-4 **Coherence**
Interference, first and second order coherence, correlation functions.

Week 2: 9/9-11 **Quantum atomic physics: 2-level atoms**
2-level systems, Rabi Flopping, Bloch sphere, Landau-Zener transitions.

Week 3: 9/16-18 **AC Stark shift**
Dressed atom picture, optical dipole trapping, optical tweezers.

Week 4: 9/23-25 **Density Matrix**
Decoherence, spontaneous emission, optical Bloch equations.

Week 5: 9/30-10/2 **Monte Carlo numerical methods**
Classical Monte Carlo, Quantum Monte Carlo, quantum jumps.

Week 6: 10/7 **Multi-level atoms**
Selection rules, fine and hyperfine structure, Zeeman effect.

-------------------------------- Fall Break ---------------------------------

Schedule (II)

Week 7: 10/14-16 **3-level atoms**
Saturation spectroscopy, electromagnetically-induced transparency.

Week 8: 10/21-23 **Laser cooling and trapping I**
Doppler cooling, optical molasses, Sisyphus cooling.

Week 9: 10/28-30 **Laser cooling and trapping II**
Resolved sideband cooling of ions, magnetic trapping, RF evaporation.

Week 10: 11/4-6 **Photons I: Quantization of the electromagnetic field**
Introduction to field theory: quantization of the electromagnetic field.

Week 11: 11/11-13 **Photons II: Quantization of the electromagnetic field**
Atom-photon interactions, photon squeezing, Casimir force.

Week 12: 11/18-20 **Quantum gases**
2nd quantization, atom interactions, Bose-Einstein condensation, Thomas-Fermi.

------------------------------- Fall Break --------------------------------

Schedule (III)

Week 13: 11/25 Atom interferometry & quantum sensing

Superpositions of position and momentum states, atomic shot noise. **Draft of final papers due on 11/25.**

Week 14: 12/2-4 Spin squeezing & quantum information

Heisenberg limit, spin squeezing, entanglement, quantum Fourier transform. **UG oral presentations on 12/2. Final papers due on 12/4.**

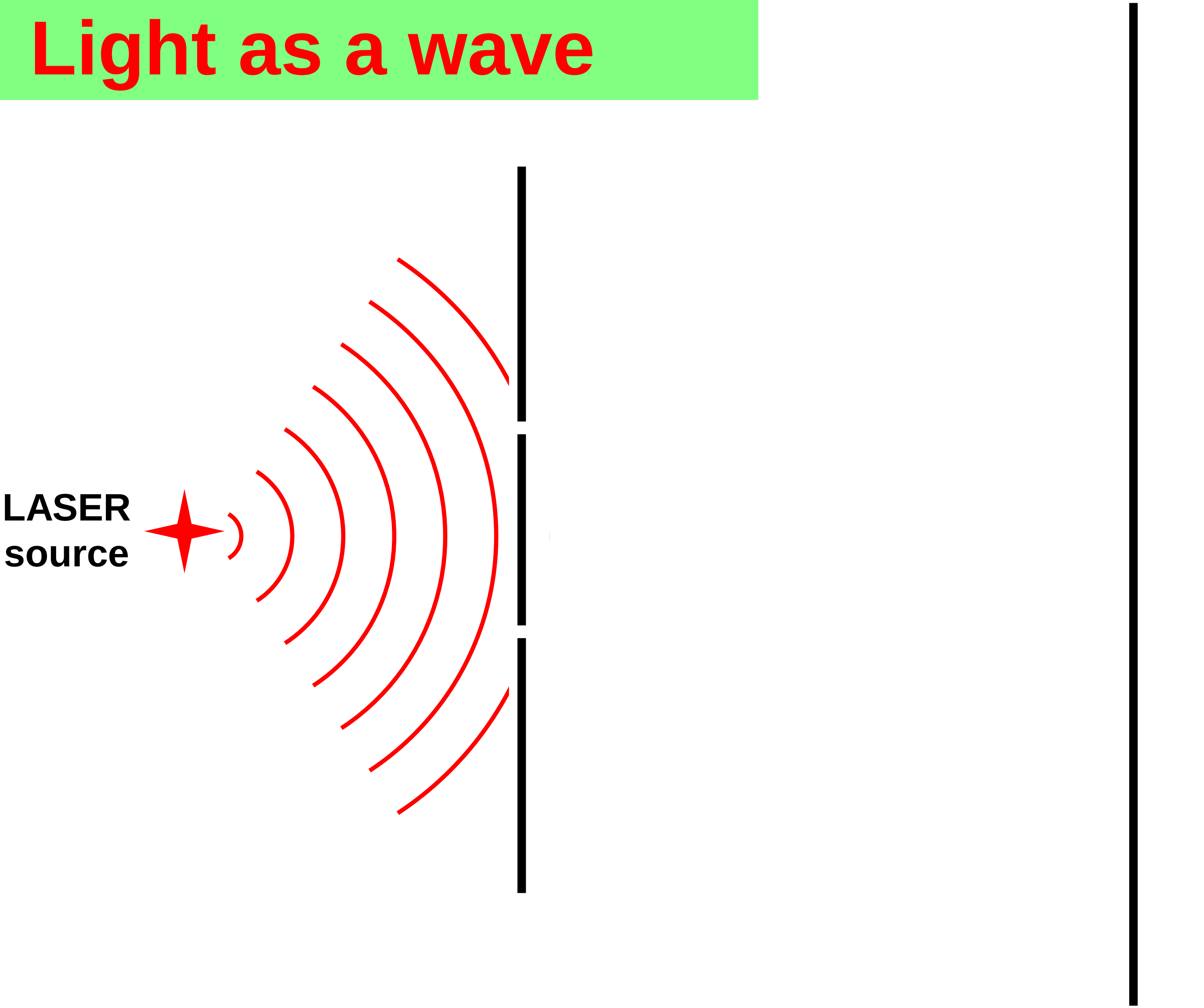
December 11, 2025, 9 am-noon Final Exam (graduate students only)

Quantum Mechanics, Atoms, and Photons

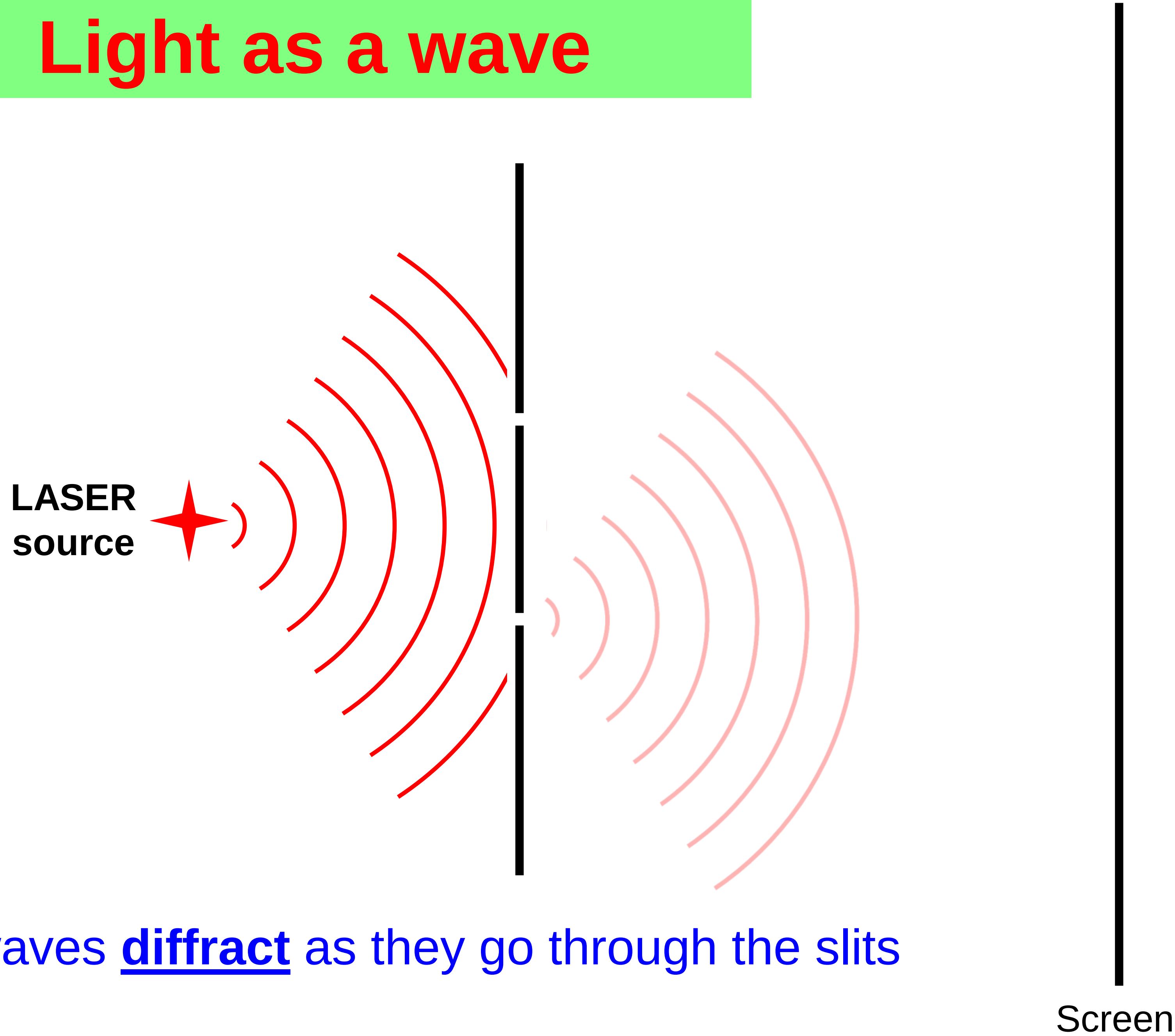
Review and Questions

1. What do you know about light and photons?
2. What do you know about atoms?
3. How was Quantum Mechanics discovered?

Light as a wave

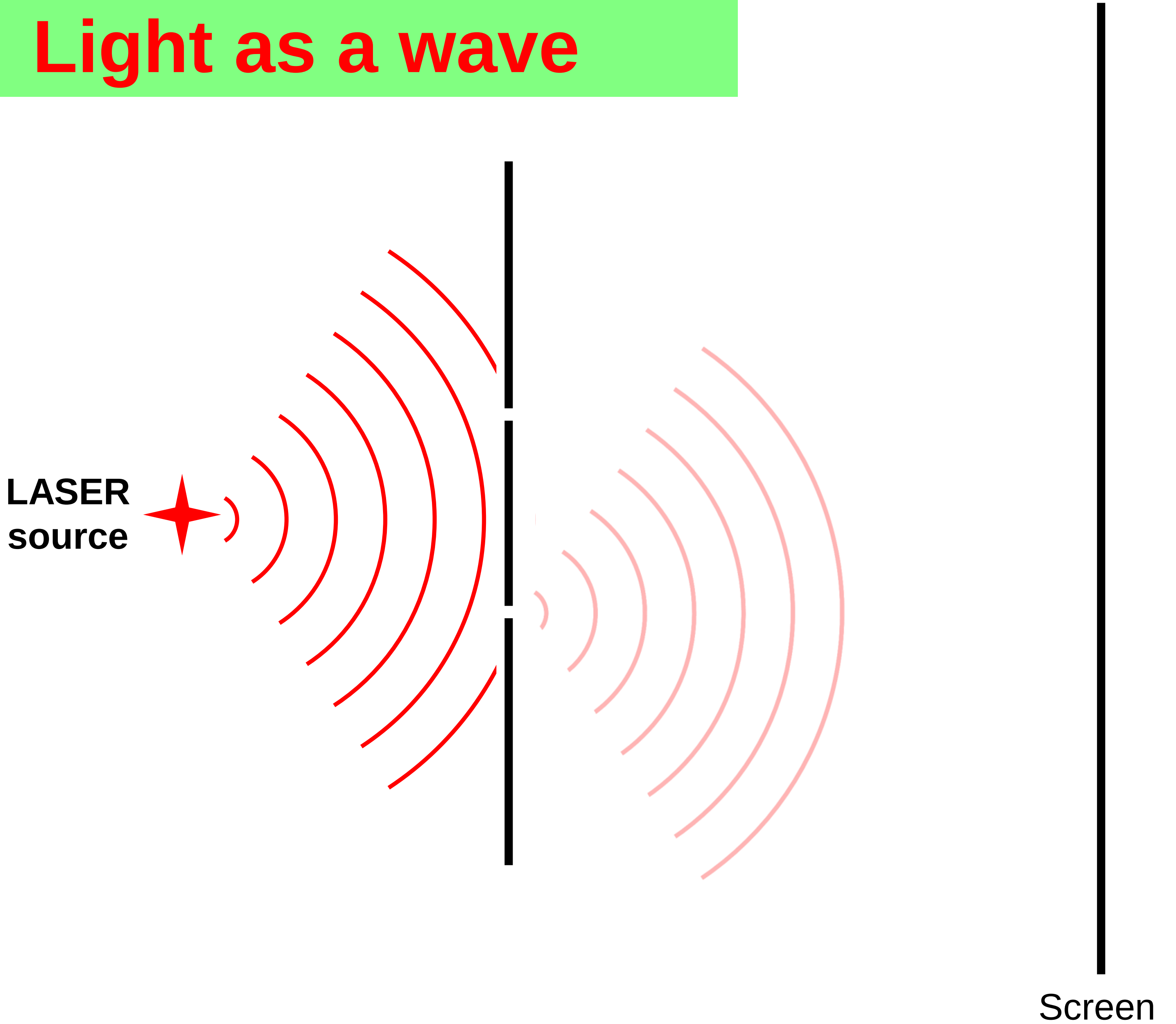


Light as a wave



Light waves **diffract** as they go through the slits

Light as a wave



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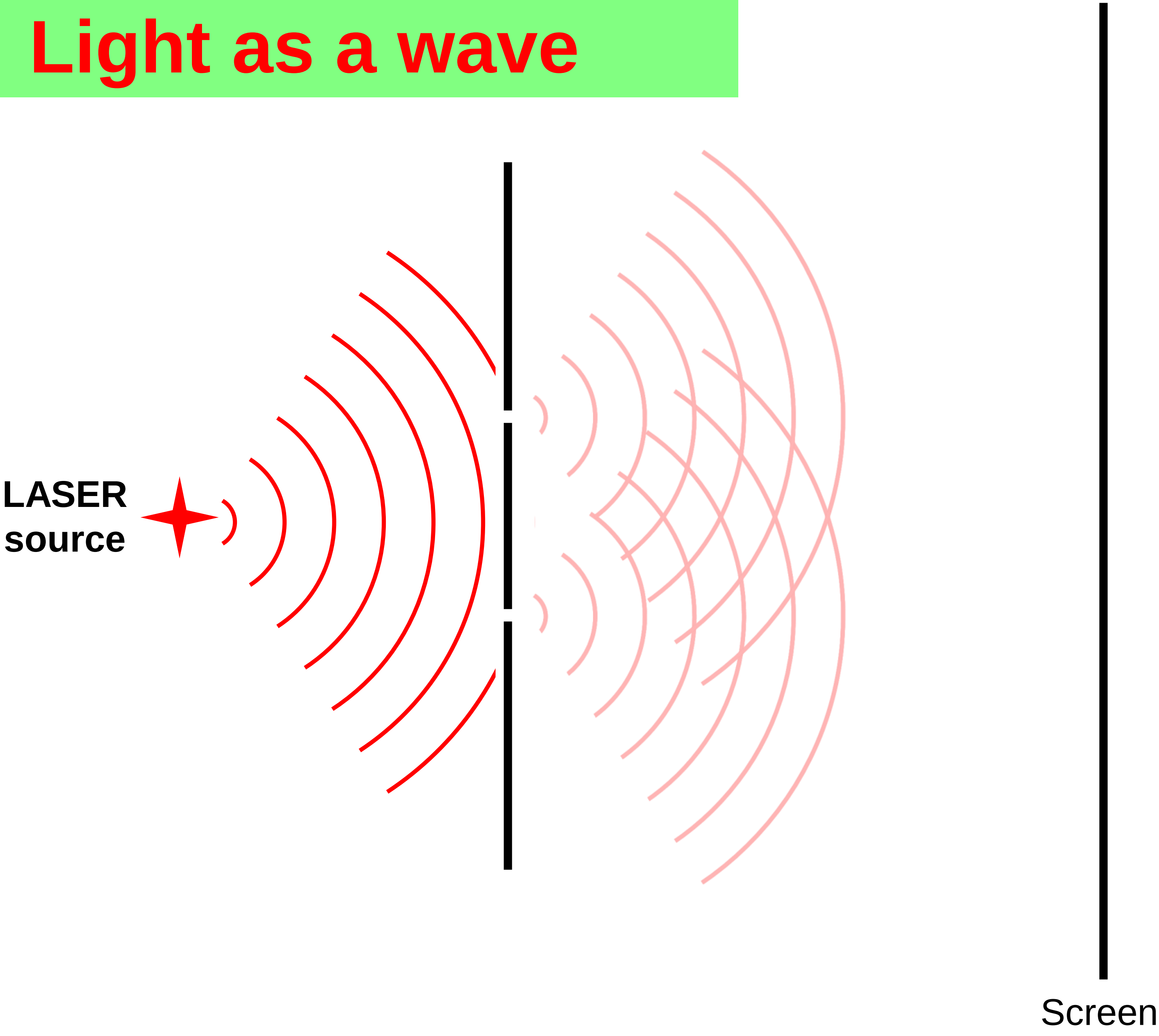

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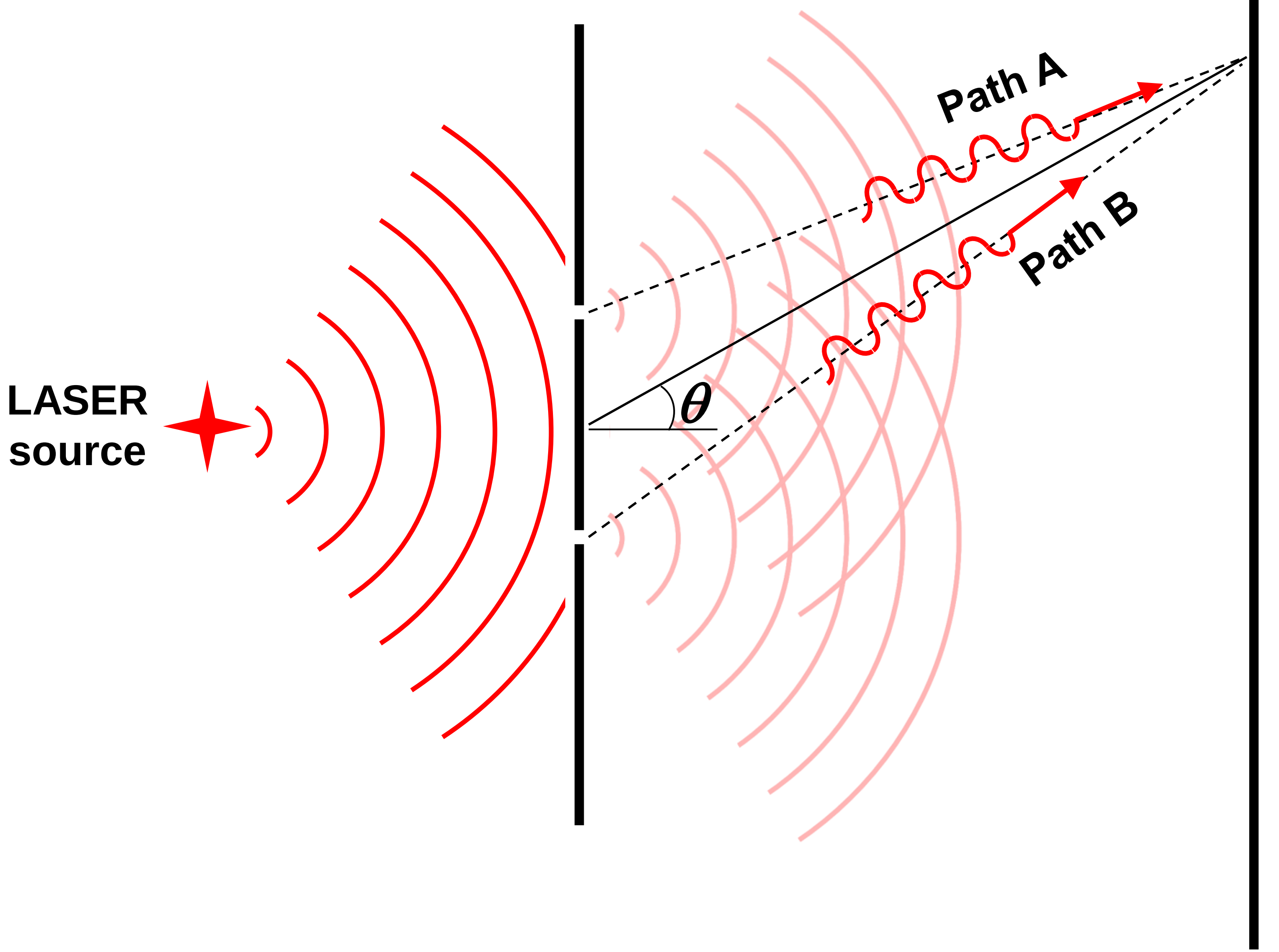

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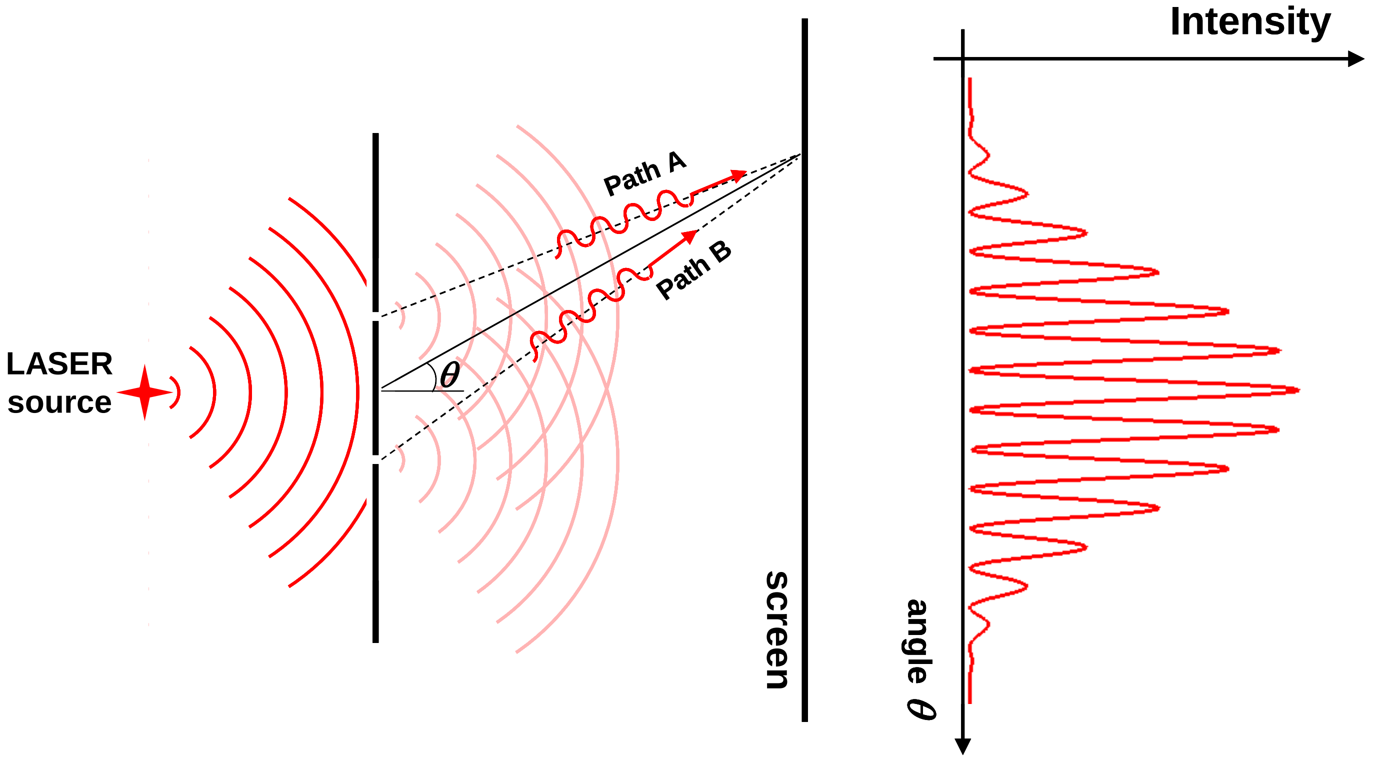
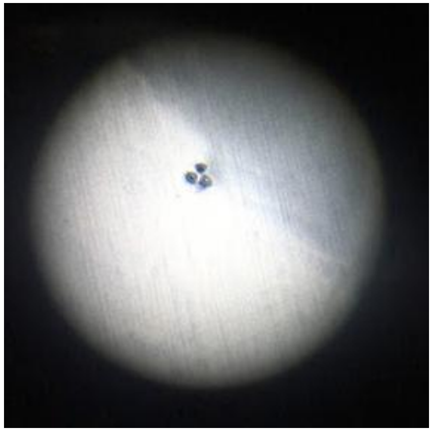
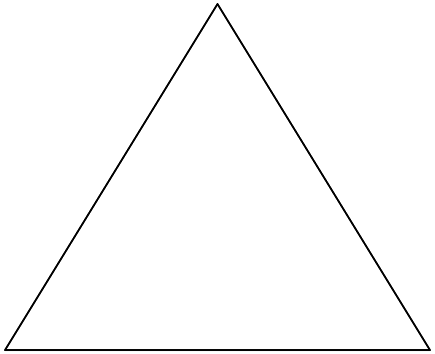
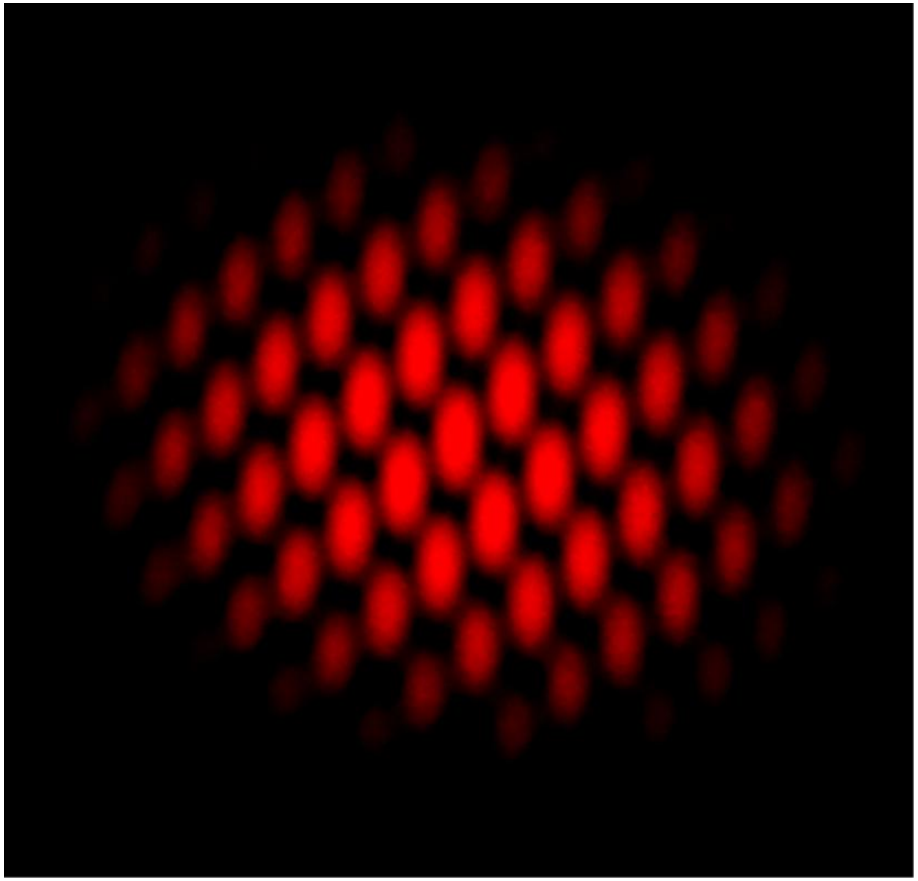


Light waves **interfere**.

3 Holes

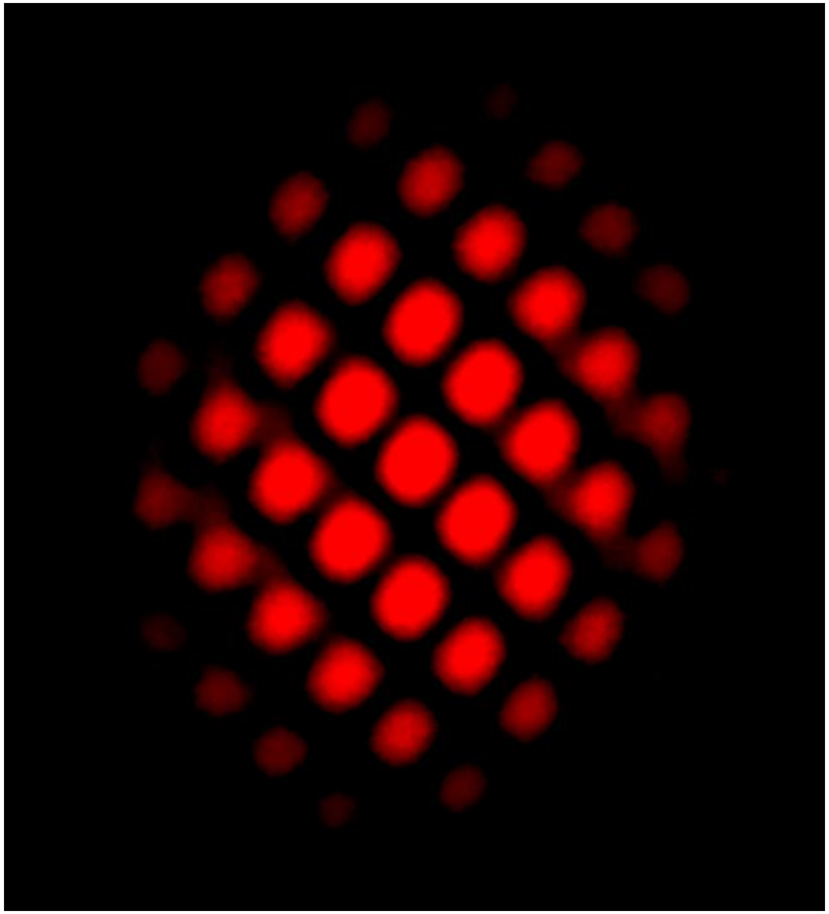






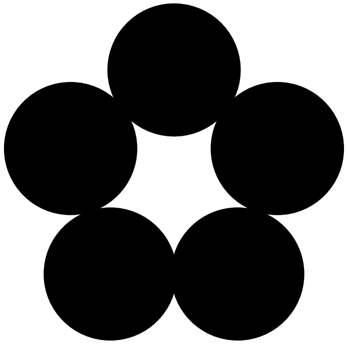
[figures from M. Frayser, W&M senior thesis, 2019]

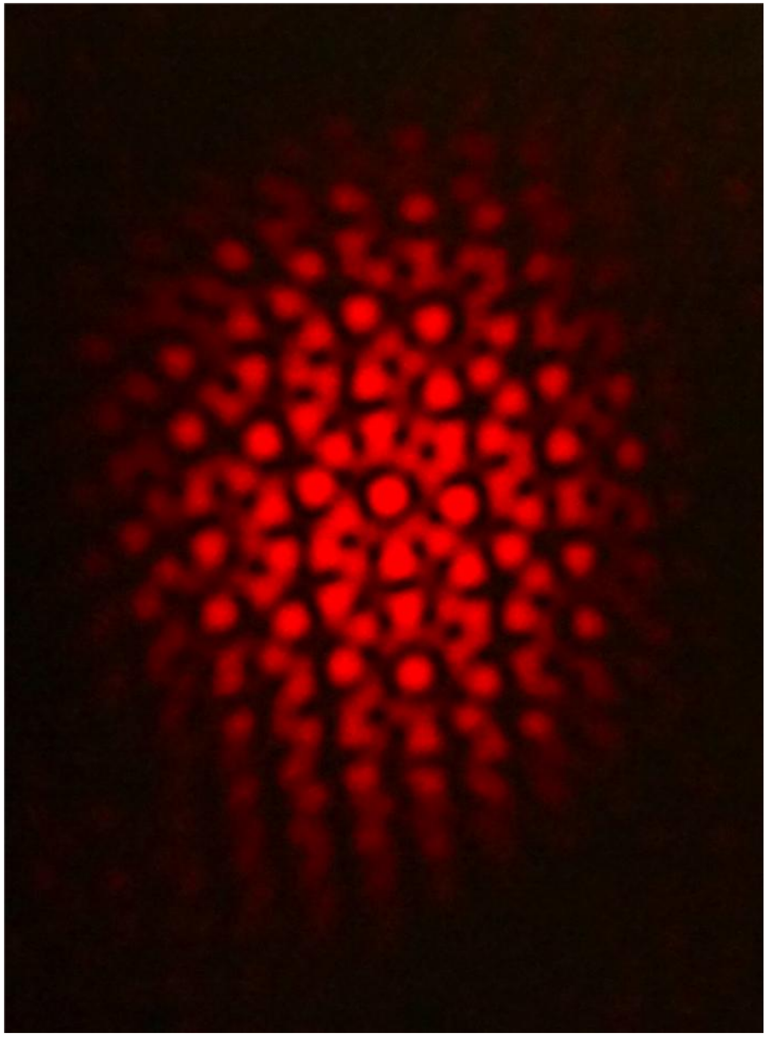
4 Holes



[figures from M. Frayser, W&M senior thesis, 2019]

5 Holes

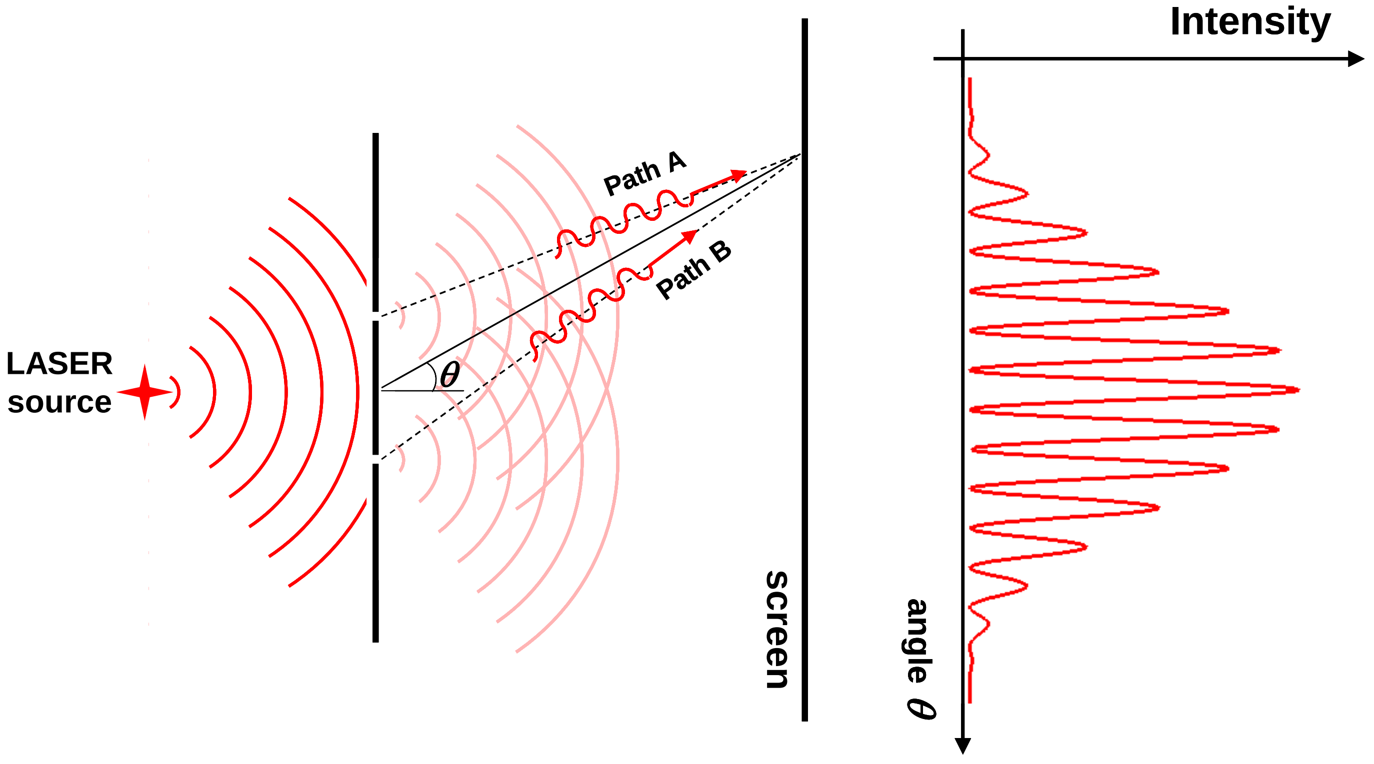




Quasi-crystal pattern → pattern does not truly repeat!!

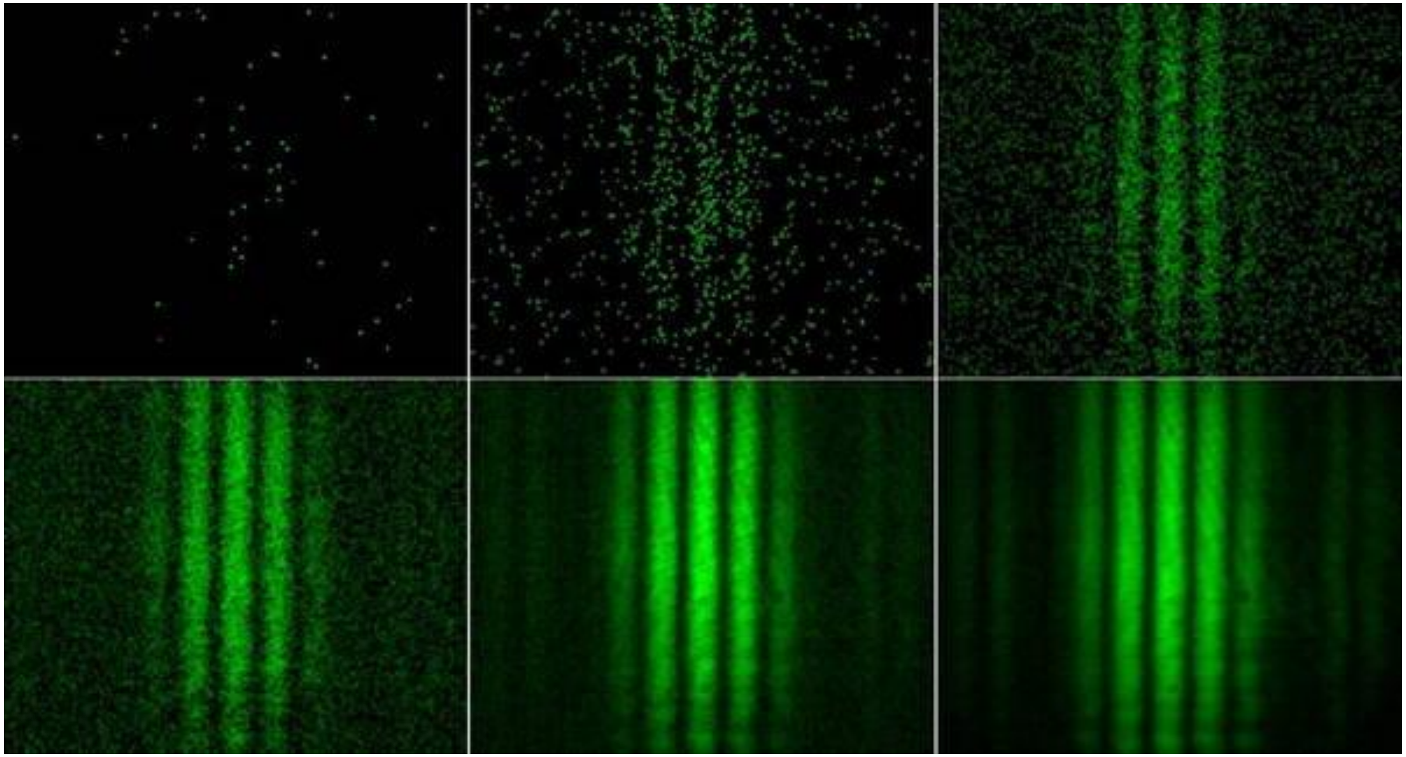
[figures from M. Frayser, W&M senior thesis, 2019]

Light as a wave



Light waves **interfere**.

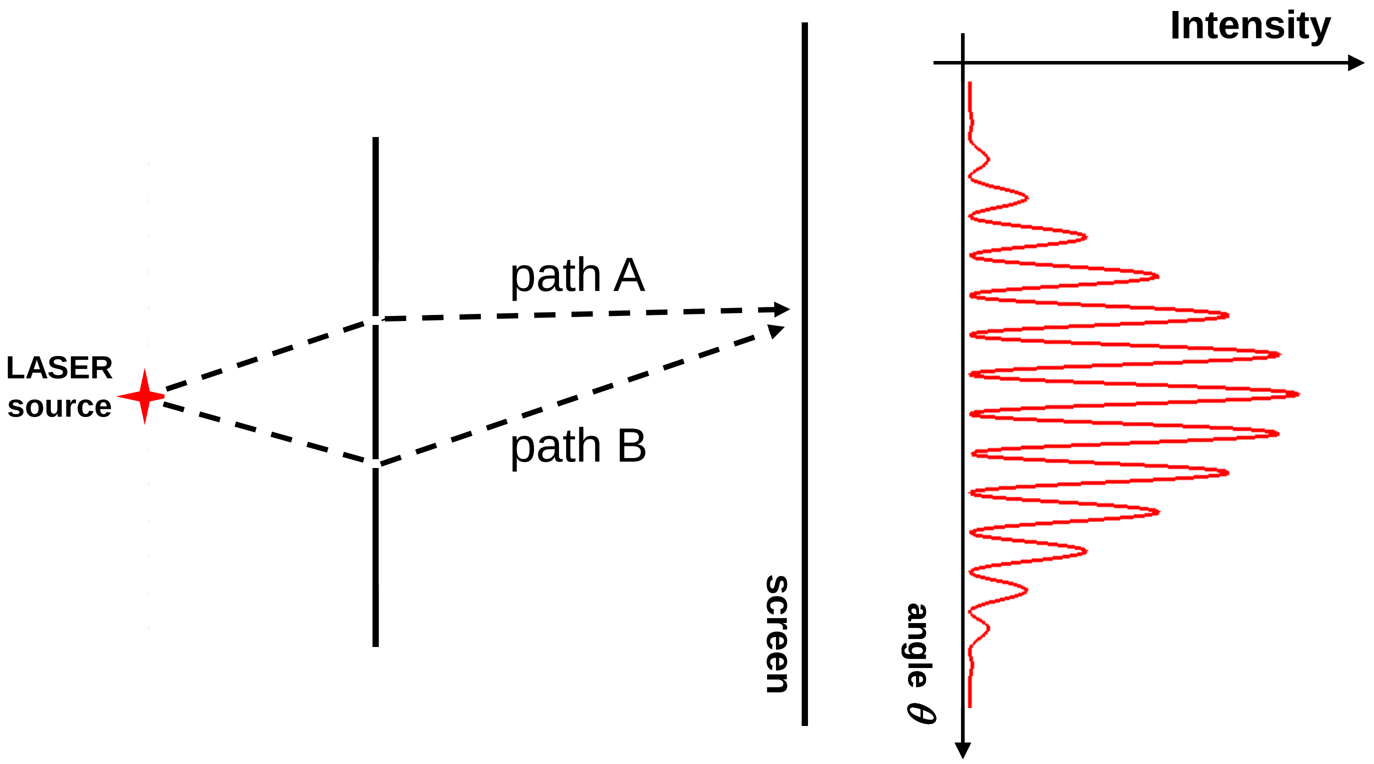
Also works for single photons !!!



[A. L. Weiss and T. L. Dimitrova, Swiss Physics Society, 2009.]

Experiment uses a CCD camera (i.e. sensor in your digital camera).

Photons follow 2 paths simultaneously



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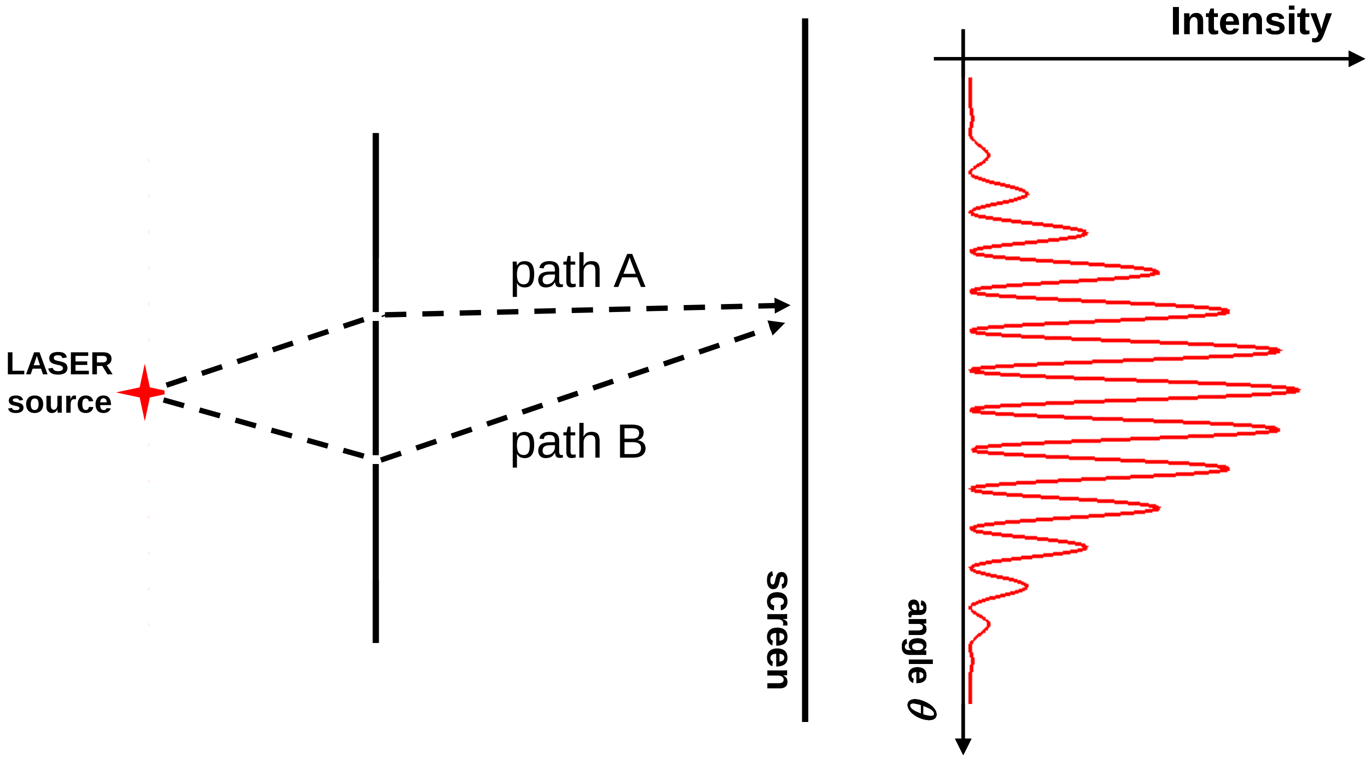
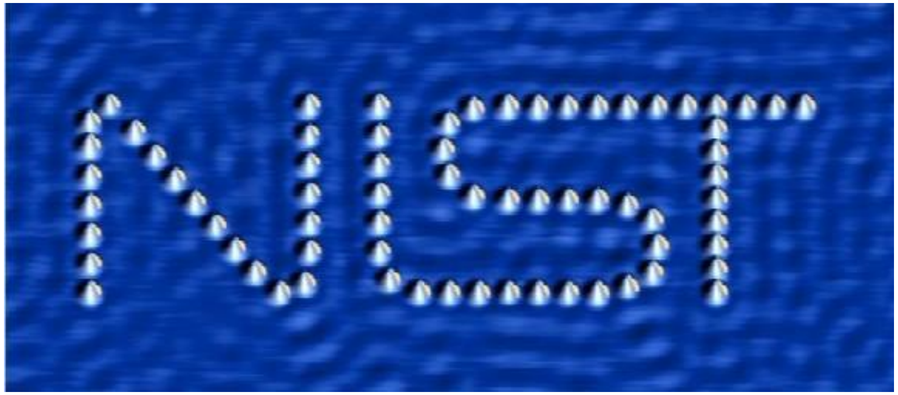


$$|\psi\rangle_{photon} = |A\rangle + e^{i\phi}|B\rangle$$

LIGHT IS A

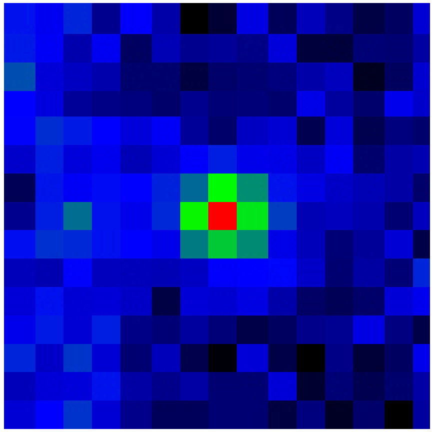
particle!

Atoms



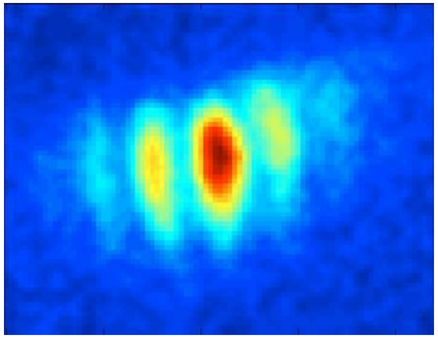
Cobalt atoms on a copper surface
(scanning tunneling microscope image)

[image from www.nist.gov]



Single Rb atom
(laser cooled and trapped)

[image from Grangier group, www.optique-quantique.u-psud.fr]



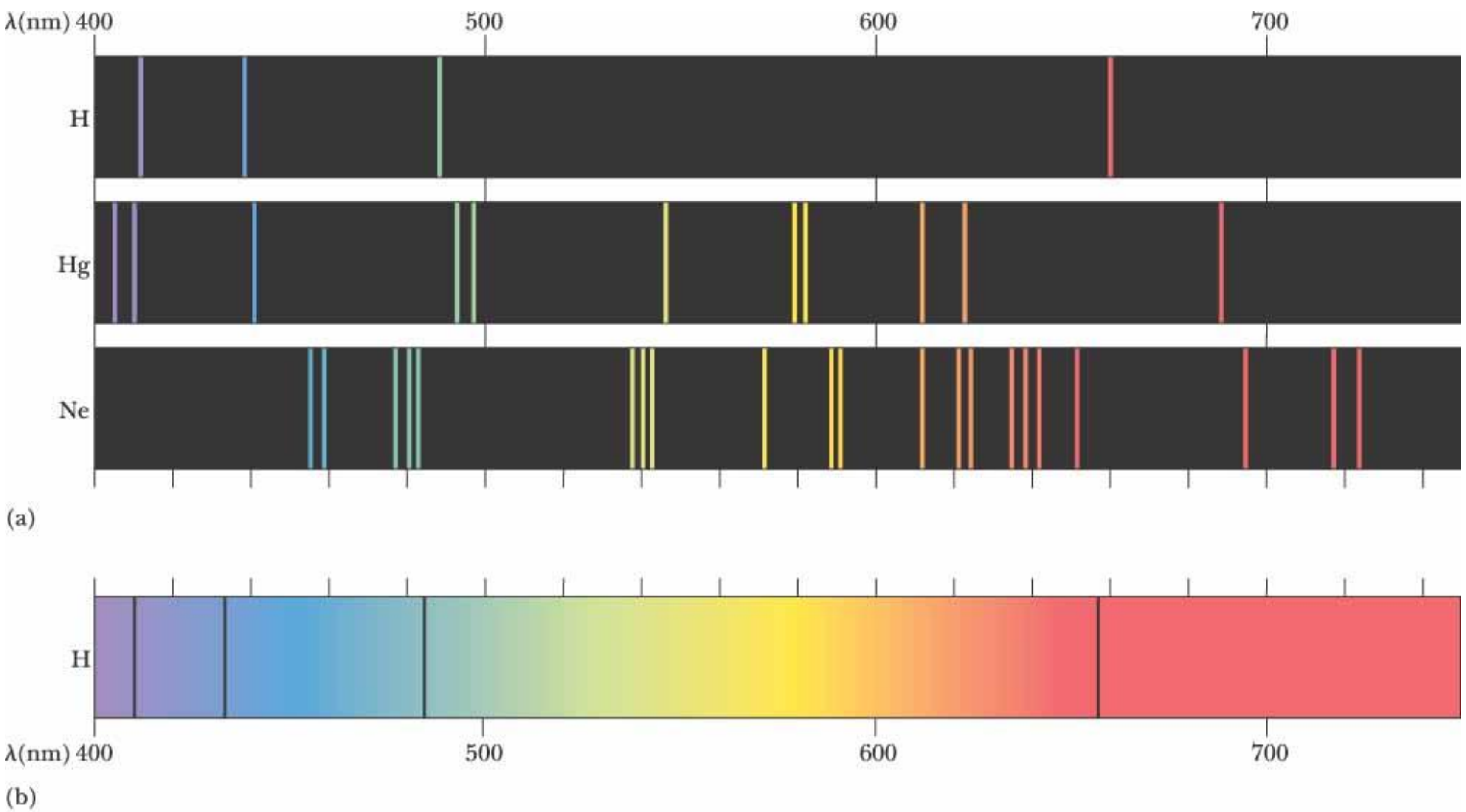
Interference of a Bose-Einstein condensate

Matter is also a

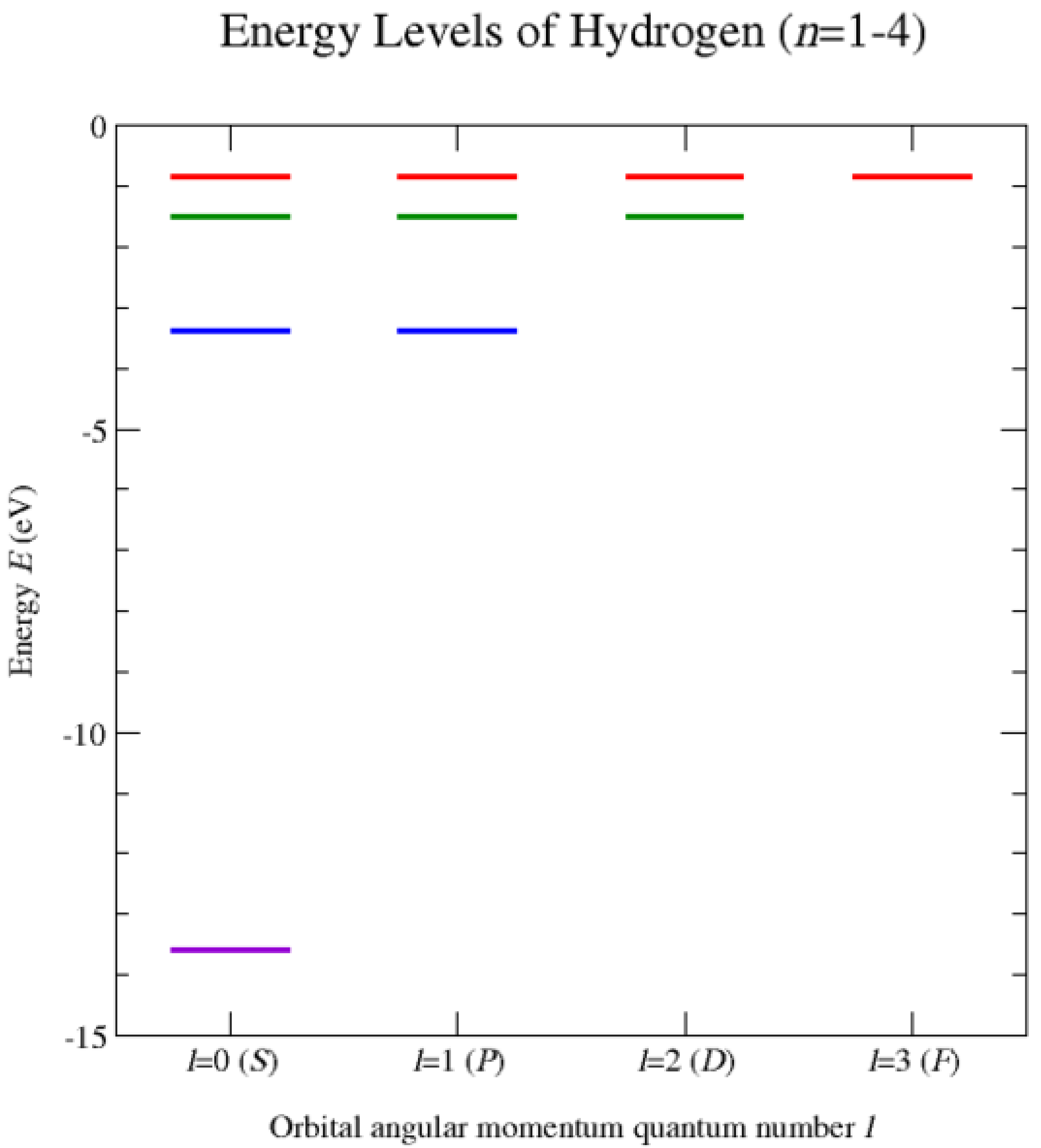
particle!

How was quantum mechanics discovered?

Atomic Emission and Absorption Spectra

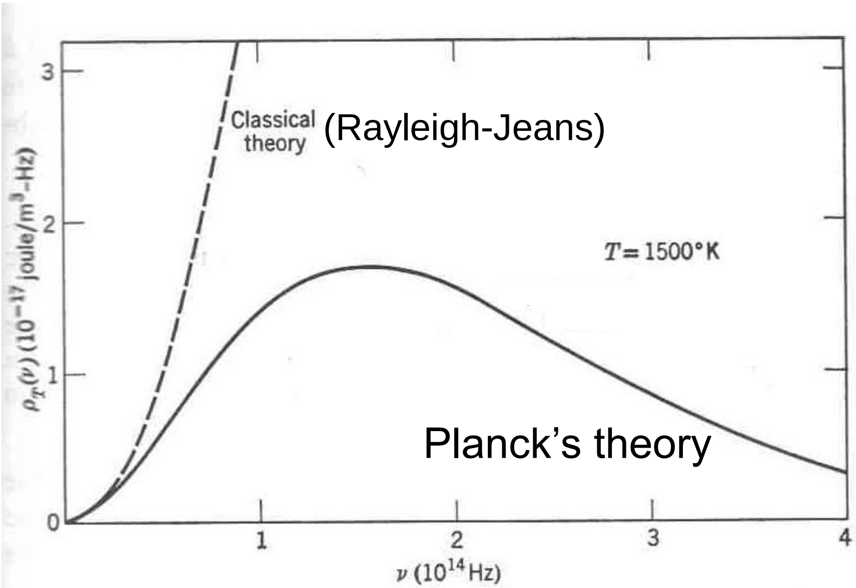


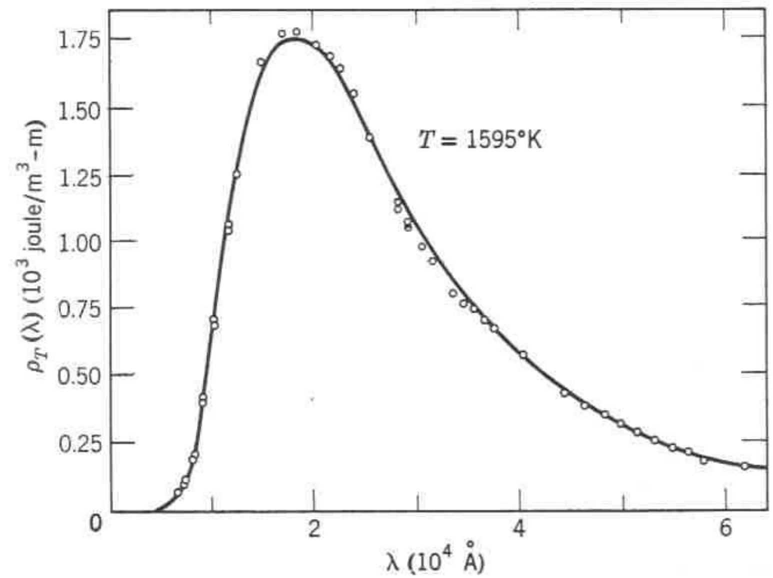
Quantum Version of Atoms



[Figure from wikimedia.org]

Blackbody Radiation: Rayleigh-Jeans vs. Planck





Experiment vs. Theory
(Coblentz data, 1916)

[figures adapted from ***Quantum Physics*** by Eisberg and Resnick, 1985.]

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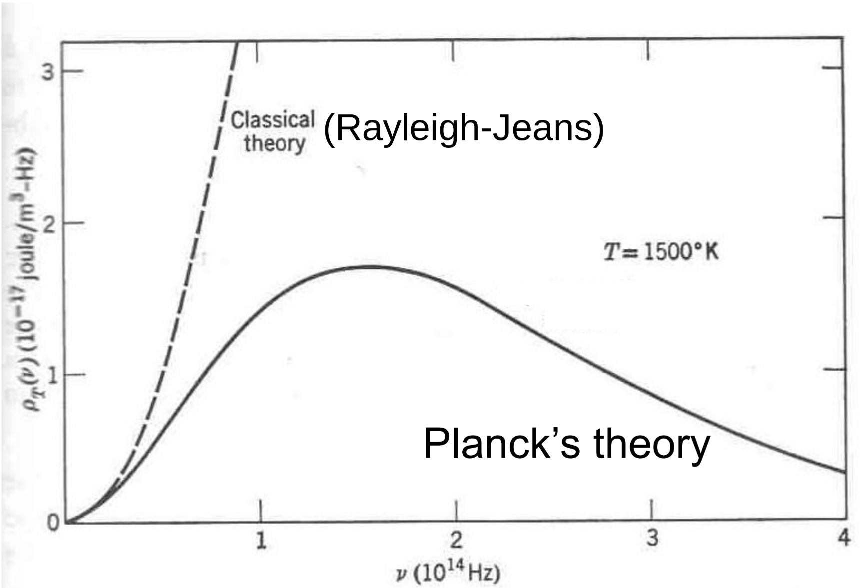
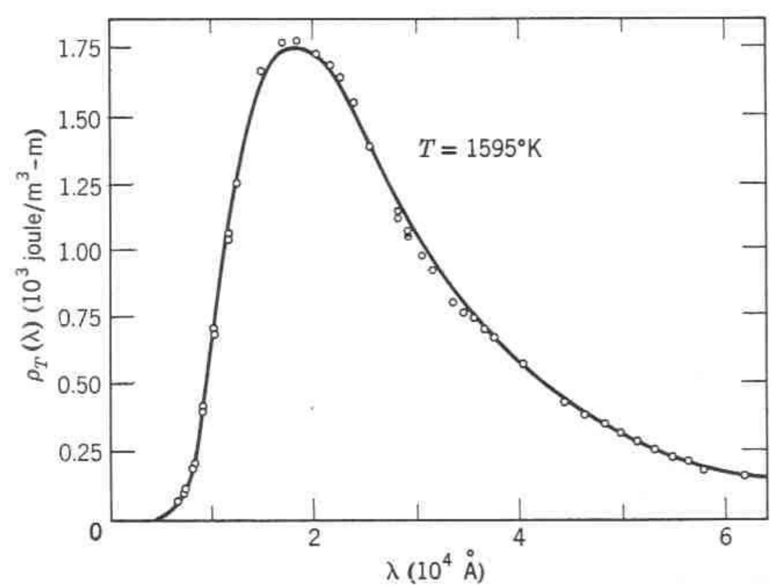


$$E = \hbar\omega$$



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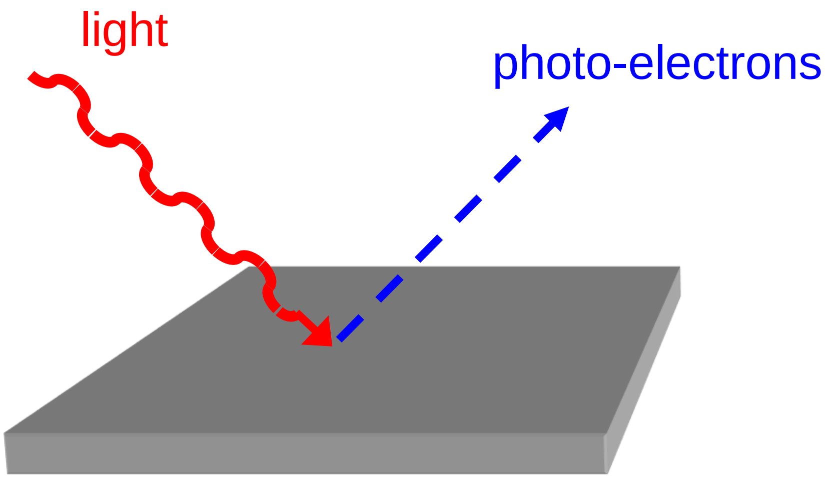

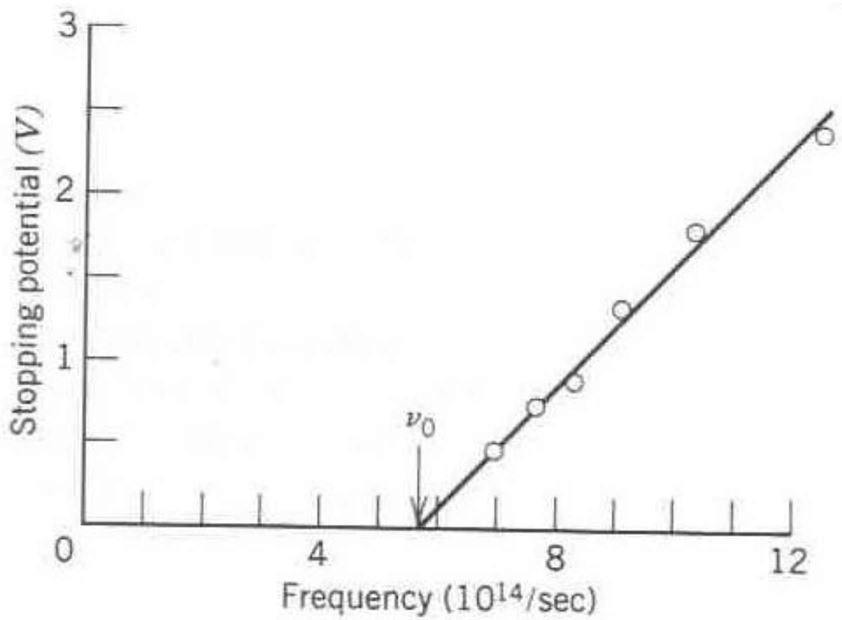

Millikan's photo-electric data for sodium (1914)

[figure adapted from ***Quantum Physics*** by Eisberg and Resnick, 1985.]

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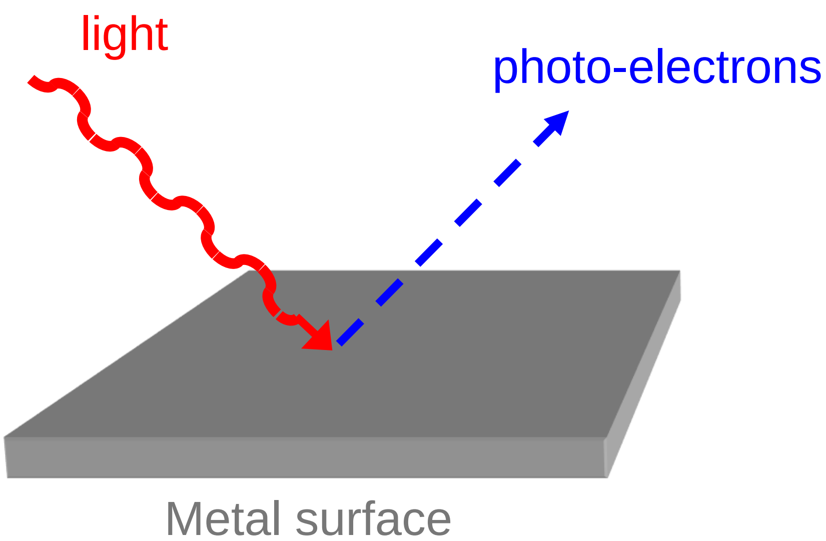

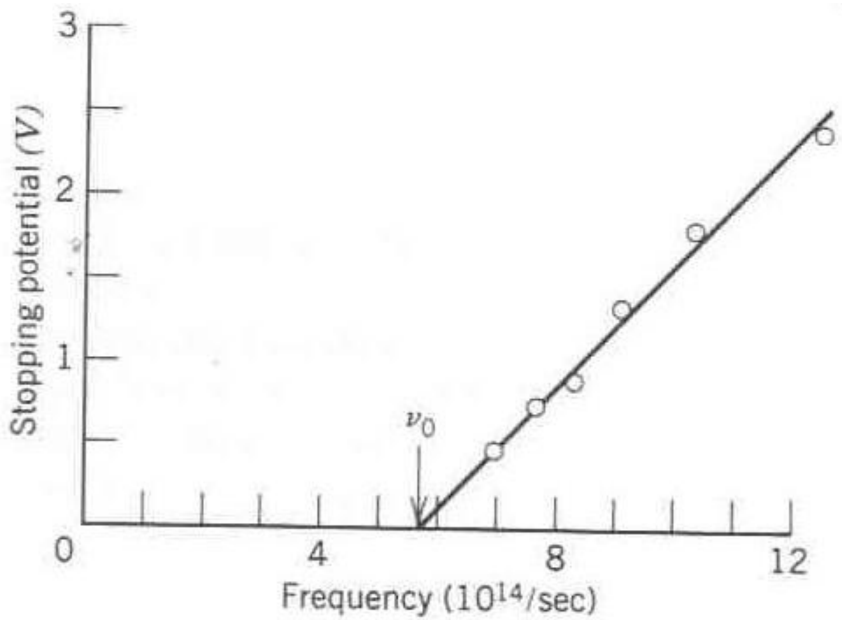

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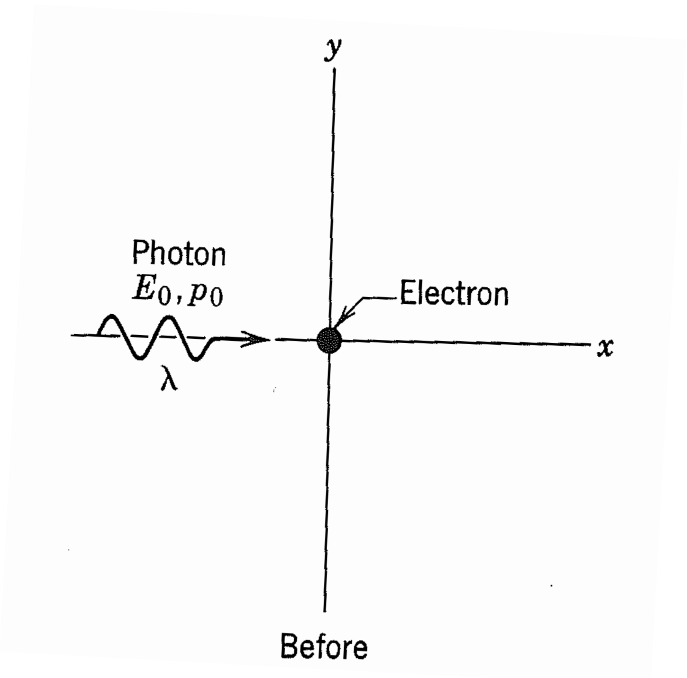
Compton Scattering



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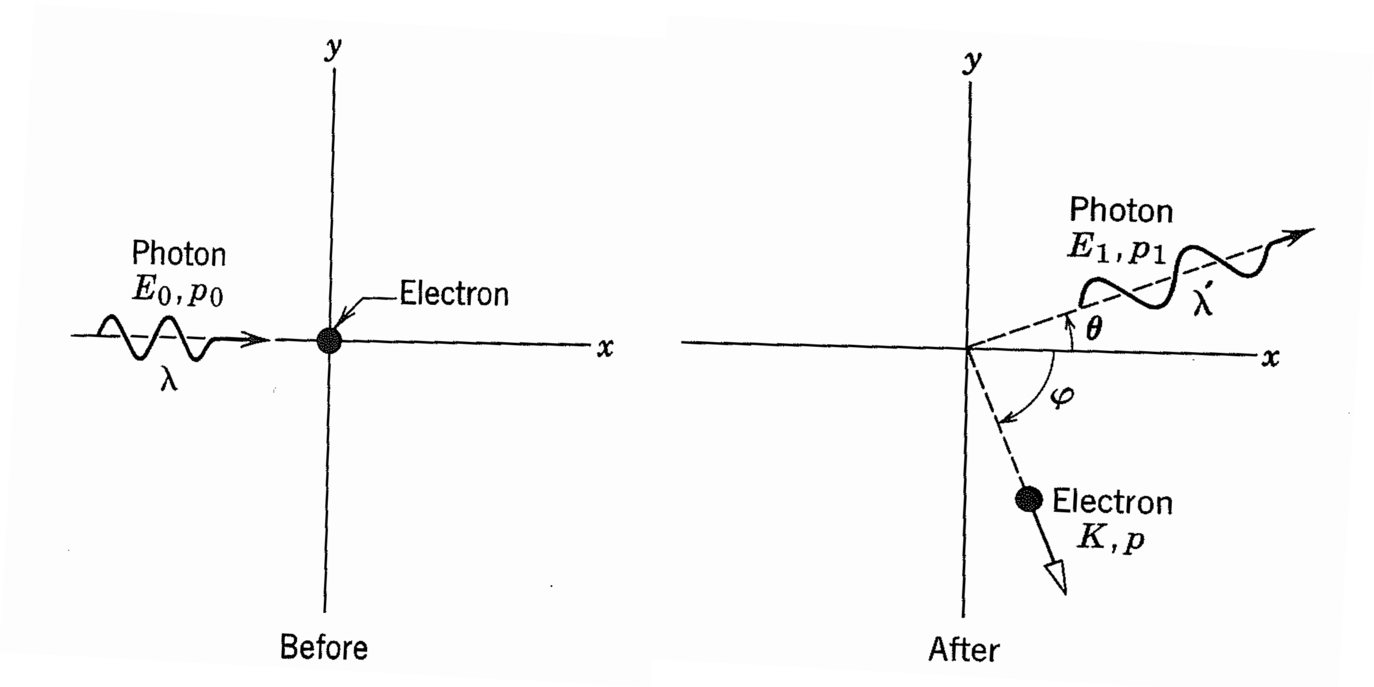

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$$\vec{p} = \hbar\vec{k}$$

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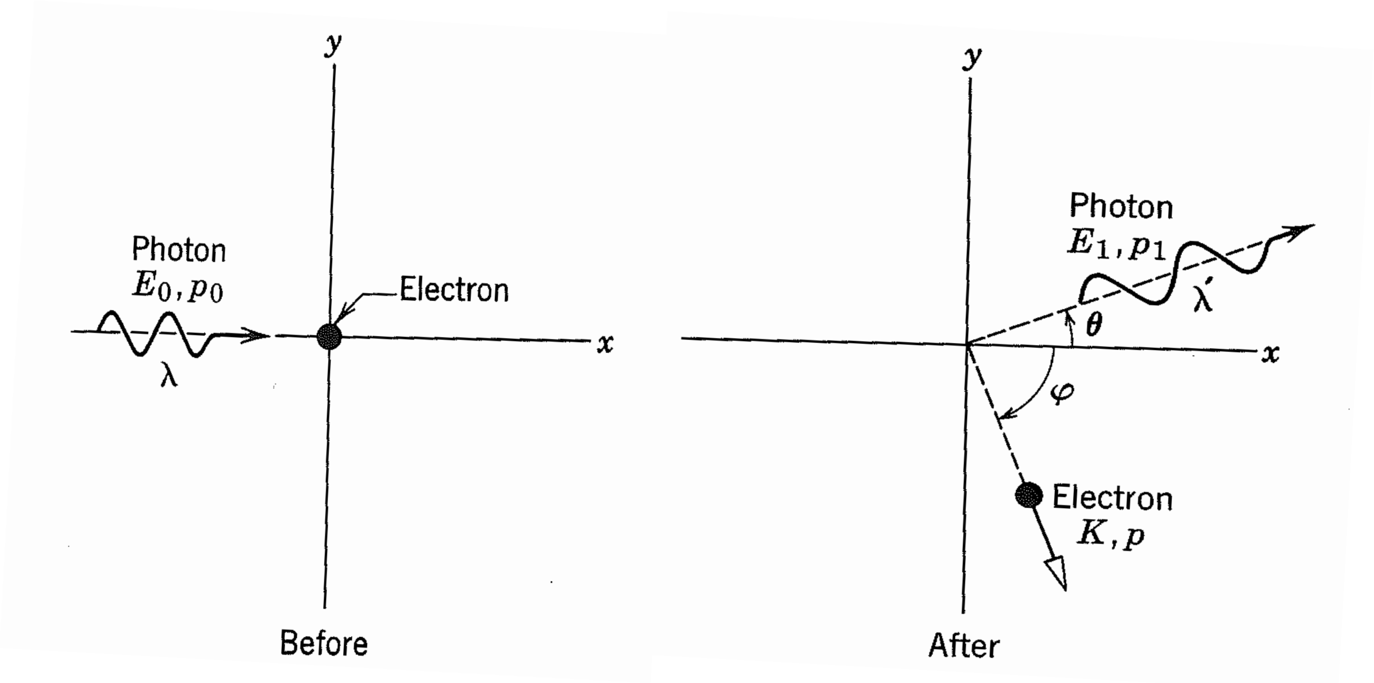

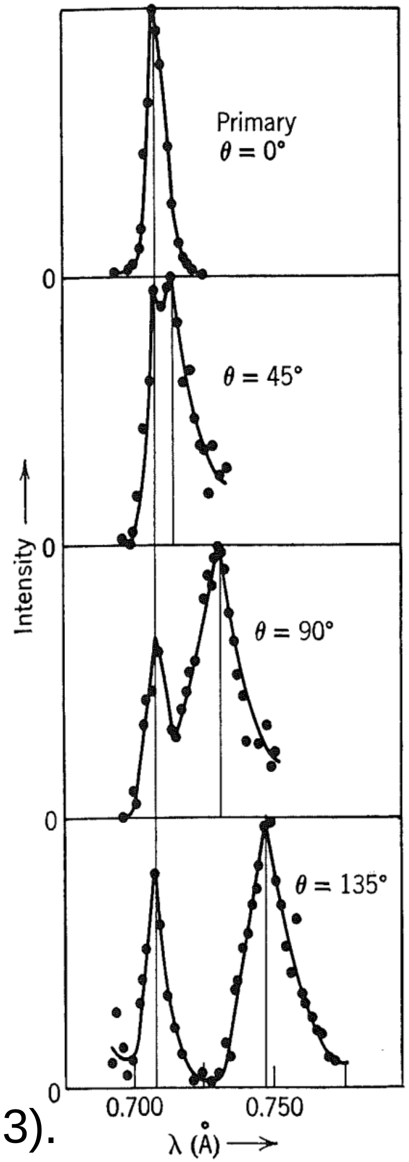

$$E = \hbar\omega$$

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Compton's data for x-ray scattering in graphite (1923).

[figures adapted from ***Quantum Physics*** by Eisberg and Resnick, 1985.]

Photons

- Essential to the discovery of Quantum Mechanics

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- What is the **Hamiltonian** of a Photon?

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- How do you treat the **phase** of a photon(s)?
- Do photons obey the **Heisenberg uncertainty relations**?

What's special about AMO Physics?

AMO Physics = Atomic, Molecular, and Optical Physics.

- Test bed for Quantum Mechanics.
- Energy resolution of internal levels at the **1 part per 10^9 – 10^{18}.**
- 100+ years of spectroscopy.
- **Frequency** measurements at **10^3-10^{15} Hz**.
- *Ab initio* calculable internal structure.
- Precision tests of QED to 9-digits (measurement to 12-digits)

Electron's g-factor: g_e = 2.002 319 304

Applications

- Time keeping.
- Inertial navigation, force sensing.
- Astronomy, nuclear, particle, and condensed matter physics.
- GPS, telecommunications, data storage.