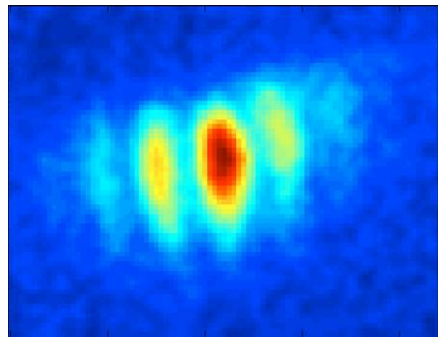
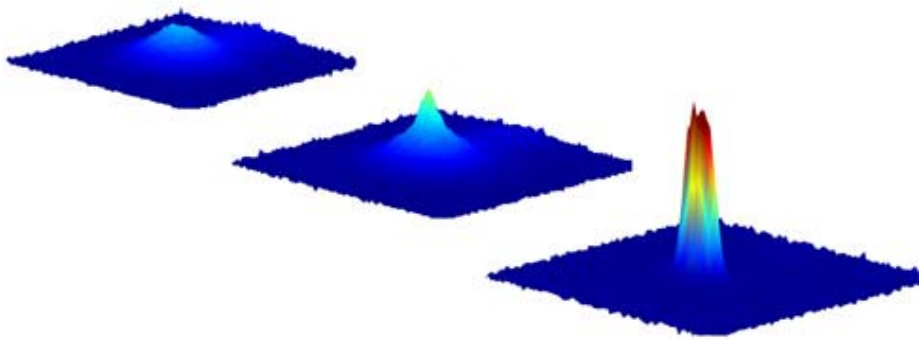
Physics 404 and Physics 690-03

Introduction to Atomic Physics and Quantum Optics





[images courtesy of Thywissen group, U of T]

Instructors

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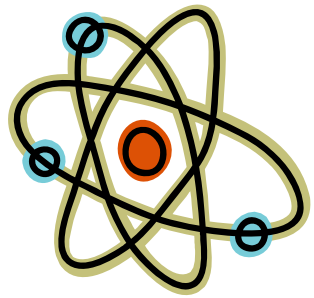
e-mail: mkivory@email.wm.edu

Office hours: Tuesdays 10-11 am

Course Objectives (I)

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



Topics:

- Classical and quantum **coherence**.
- **2-level atoms**, atom-light interactions, Bloch sphere.
- Spontaneous emission, **decoherence**.
- **Schrödinger** equation, **density matrix**, **quantum Monte Carlo**.

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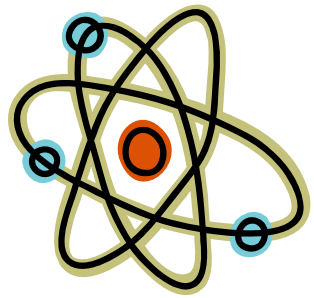

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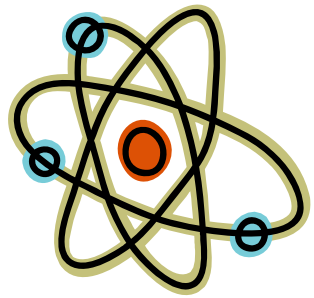

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- **Angular momentum** of light and atoms.
- **Multi-level** quantum systems.
- **Laser cooling and trapping**.
- Quantum theory of light, **dressed atoms**, squeezing.
- **Quantum gases:** Bose-Einstein condensation, atom-atom interactions.

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** (May 1, 2-5pm)

Undergraduate Grading

Problem sets	40 %
Participation	10 %
Midterm	15 %
Final paper	20 %
Oral presentation	15 %
Total	**100 %**

Graduate Grading

Problem sets	50 %
Participation	10 %
Midterm	15 %
Final Exam	25 %
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.

Schedule (I)

Week 0: 1/18-20 **Intro to Atomic Physics**
Introduction to atom-light interactions, semi-classical atomic physics.

Week 1: 1/23-27 **Coherence**
Interference, first and second order coherence, correlation functions.

Week 2: 1/30-2/3 **Quantum atomic physics: 2-level atoms**
2-level systems, Rabi Flopping, Bloch sphere, Landau-Zener transitions.

Week 3: 2/6-10 **AC Stark Shift**
Dressed atom picture, optical dipole trapping, optical tweezers.

Week 4: 2/13-17 **Density Matrix**
Decoherence, spontaneous emission, optical Bloch equations.

Week 5: 2/20-24 **Monte Carlo numerical methods**
Classical Monte Carlo, Quantum Monte Carlo.

Week 6: 2/27-3/2 **Multi-level atoms**
Selection rules, fine and hyperfine structure, Zeeman effect.

---------- Spring Break ----------

Schedule (II)

Week 7: 3/12-16 **3-level atoms**
Saturation spectroscopy, electromagnetically-induced transparency.

Week 8: 3/19-23 **Laser Cooling and Trapping I**
Doppler cooling, optical molasses, Sysiphus cooling.

Week 9: 3/26-30 **Laser Cooling and Trapping II**
Resolved sideband cooling of ions, magnetic trapping, RF evaporation.

Week 10: 4/2-6 **Photons I: Quantization of the E-M Field**
Introduction to field theory: quantization of the electromagnetic field.

Week 11: 4/9-13 **Photons II: Quantization of the E-M Field**
Atom-photon interactions, photon squeezing, Casimir force.

Week 12: 4/16-20 **Bose-Einstein Condensation I**
2nd quantization of QM, atom-atom interactions, Bose-Einstein condensation. Final papers due on 4/22. Undergraduate oral presentations.

Week 13: 4/23-27 **Bose-Einstein Condensation II**
Gross-Pitaevskii equation, Thomas-Fermi, vortices, Bogoliubov spectrum.

May 1, 2012, 2-5pm **Final Exam (graduate students only)**

Quantum Mechanics, Atoms, and Photons

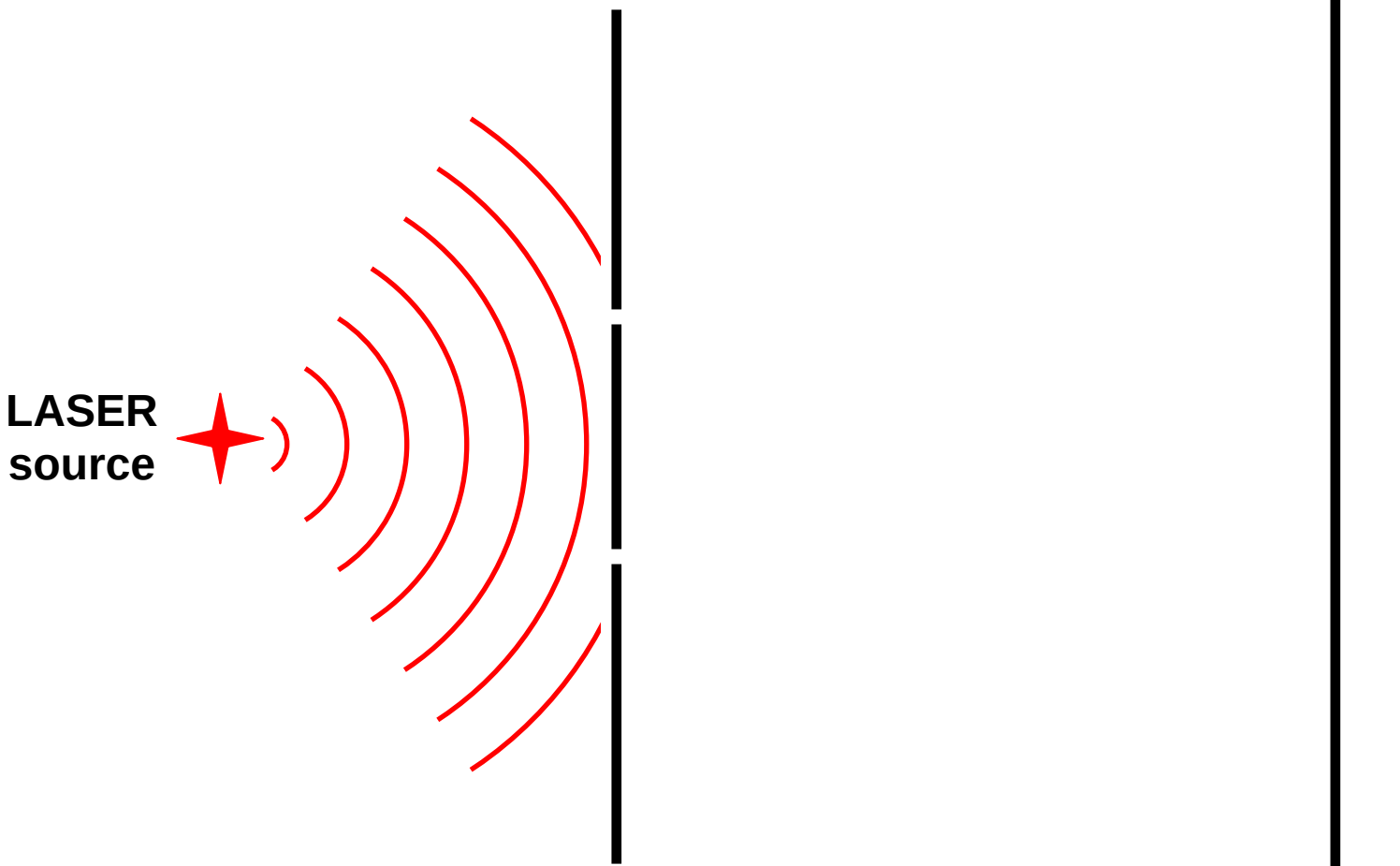
Review and Questions

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



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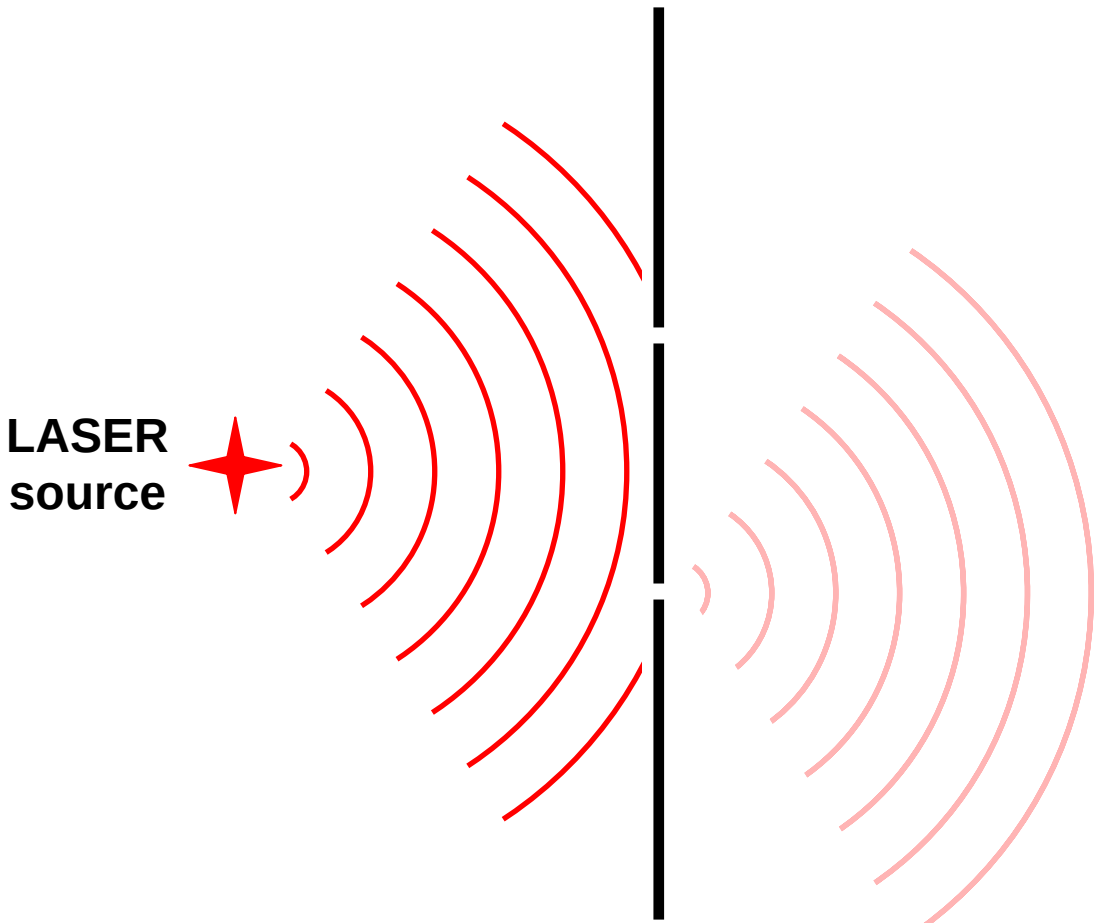
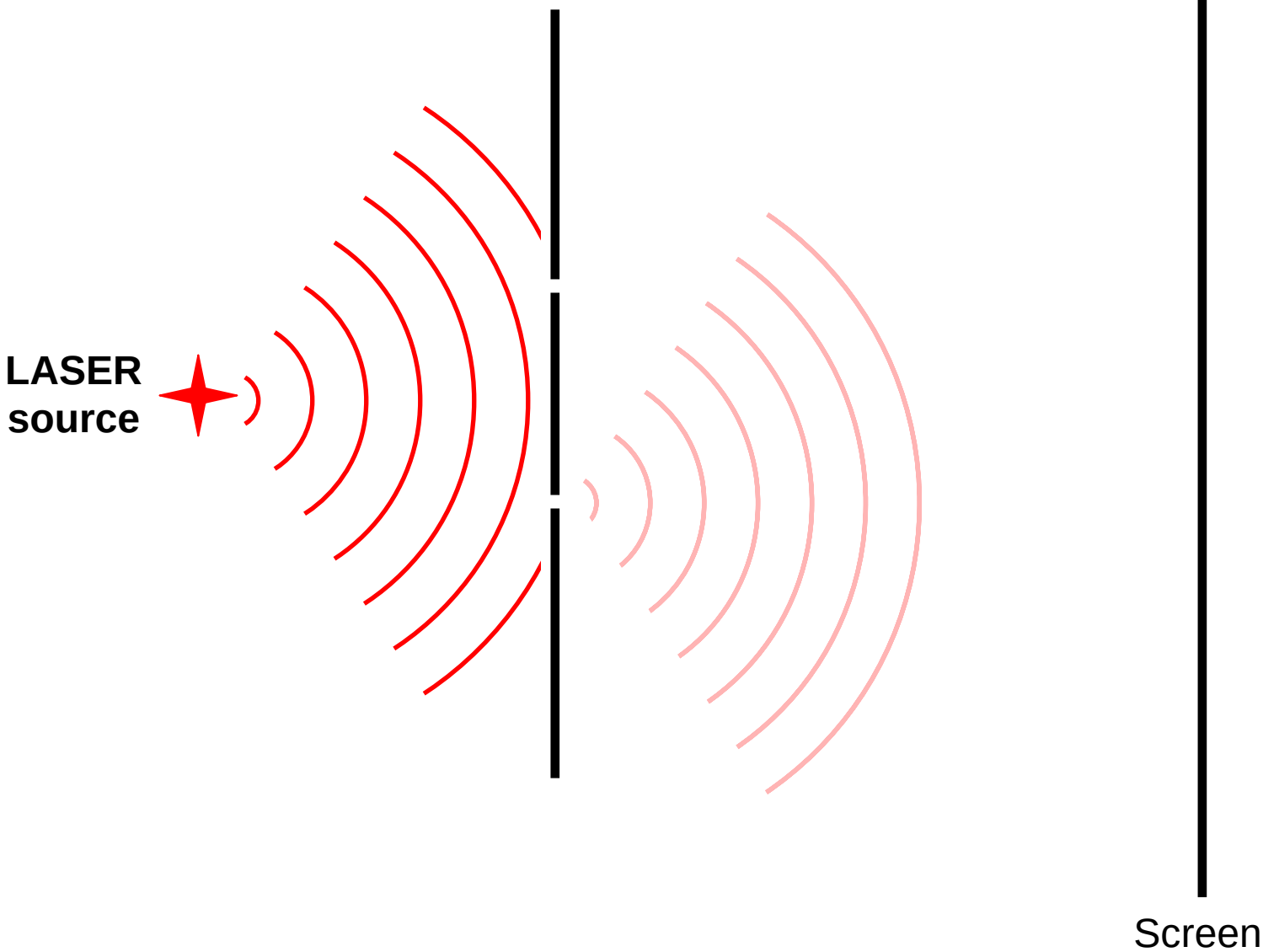


Light waves **diffract** as they go through the slits

Screen

Light as a wave



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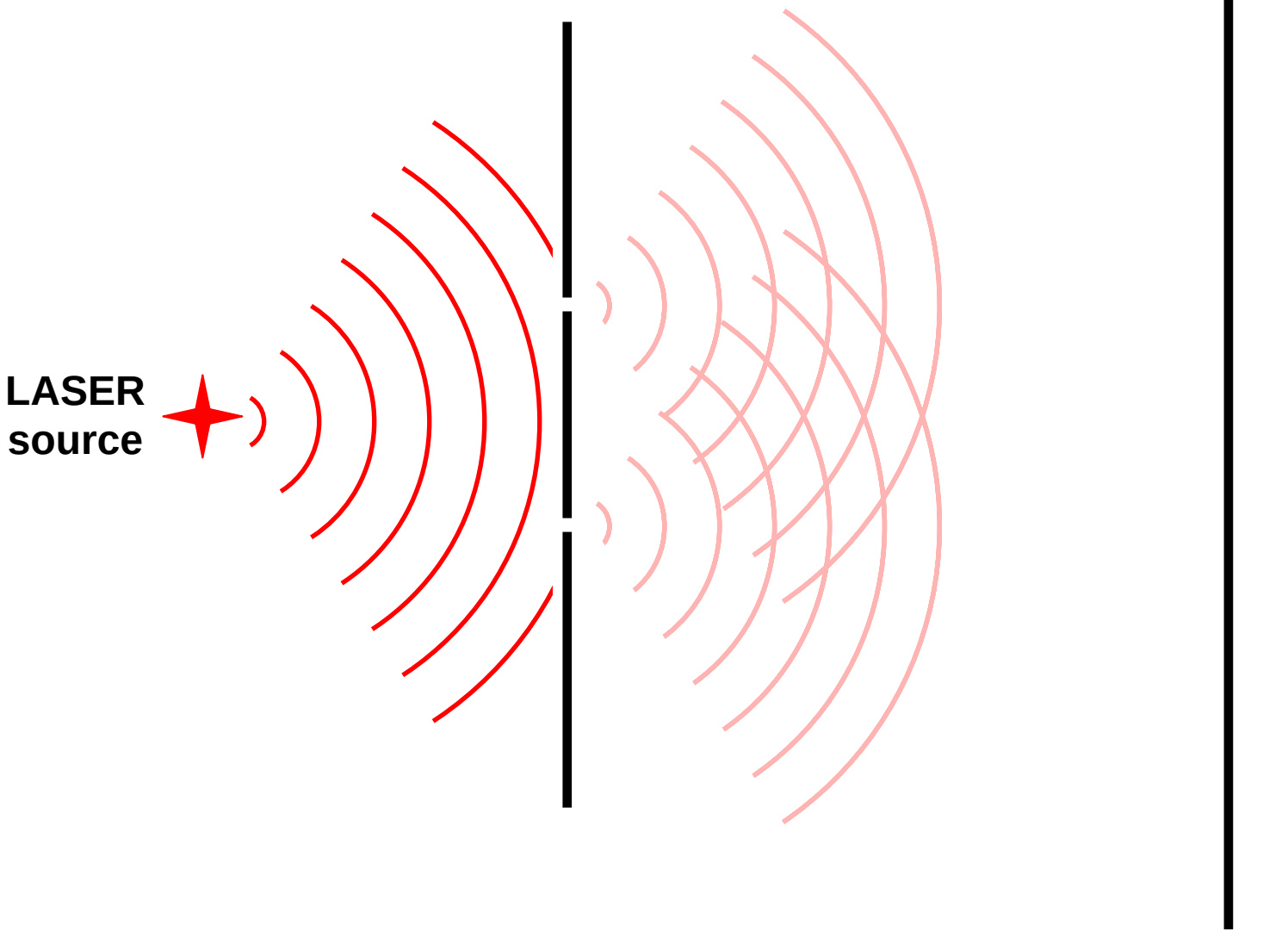

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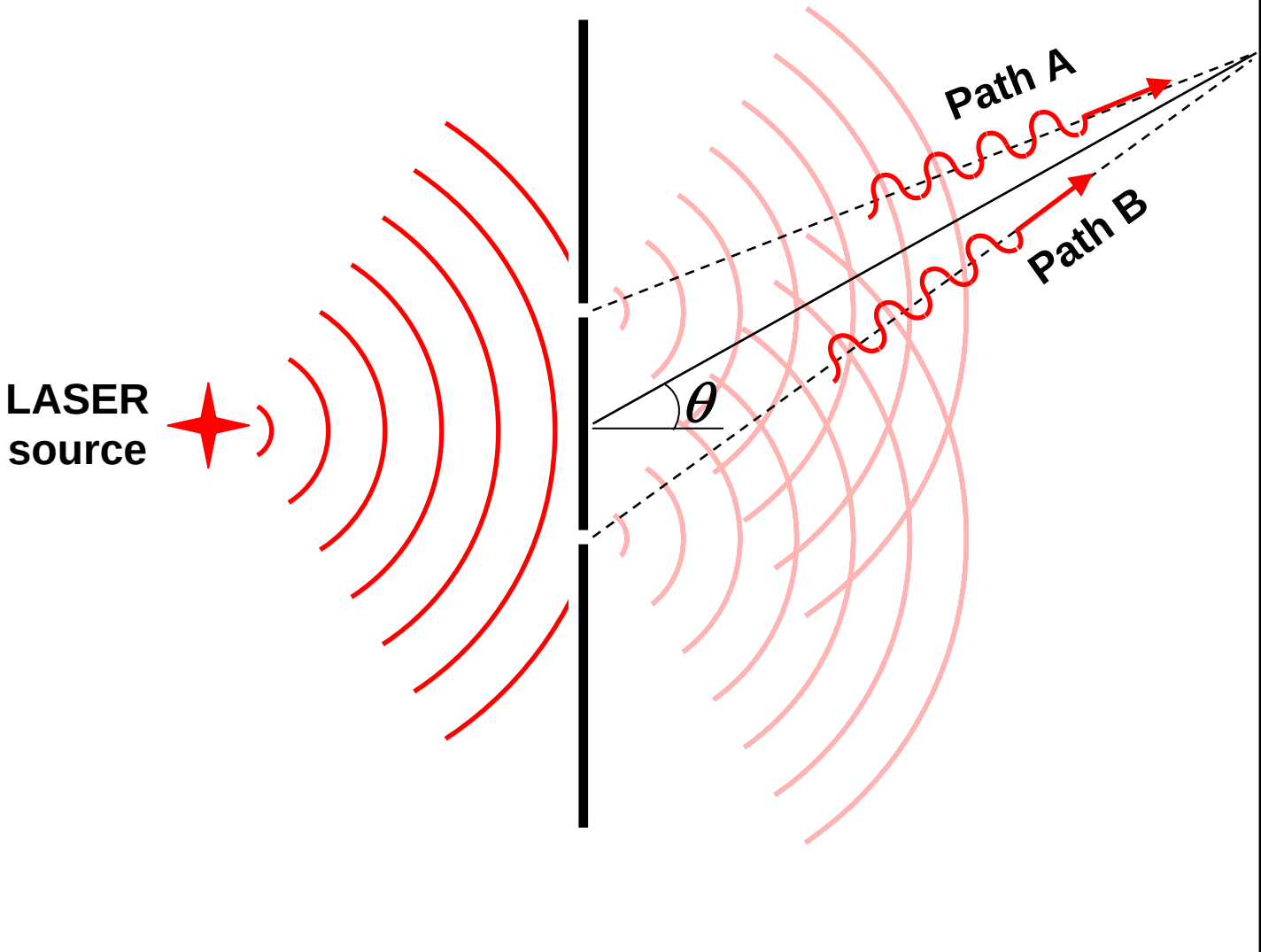

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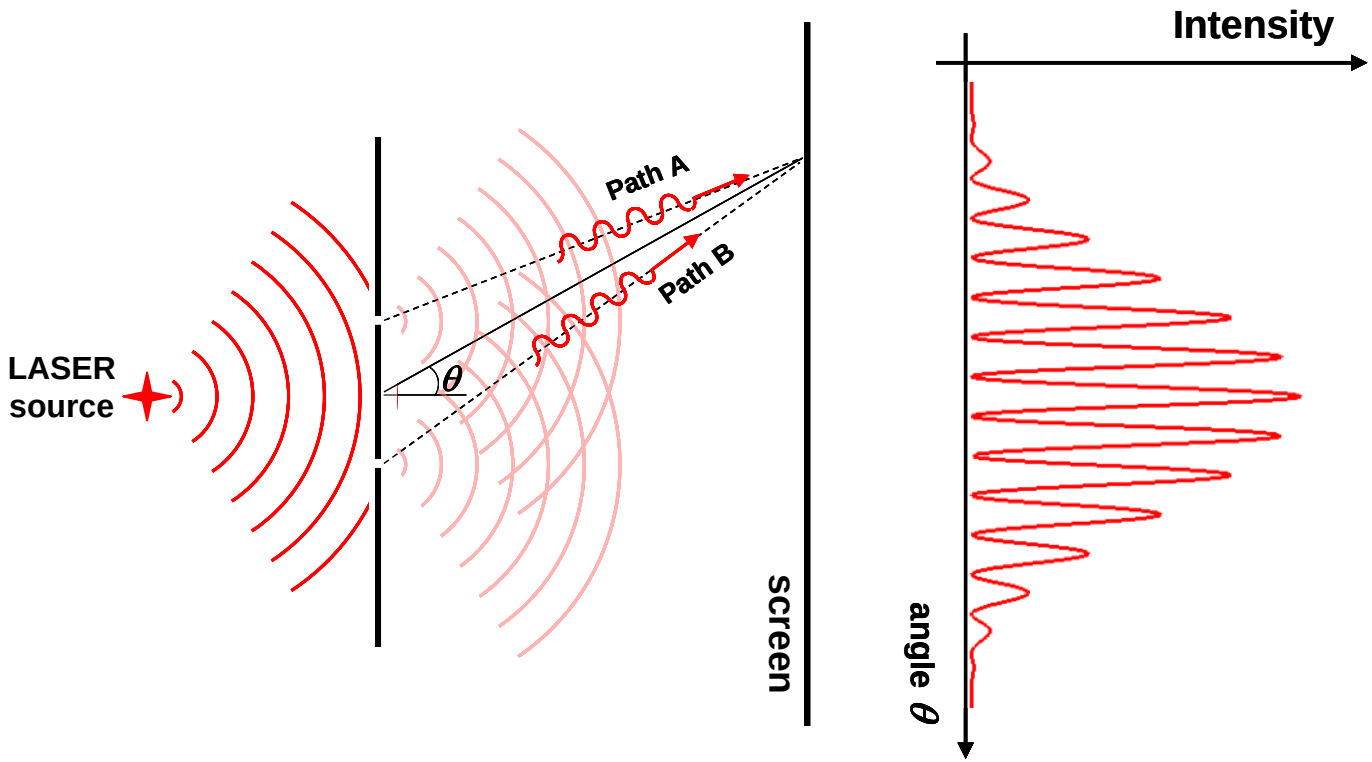
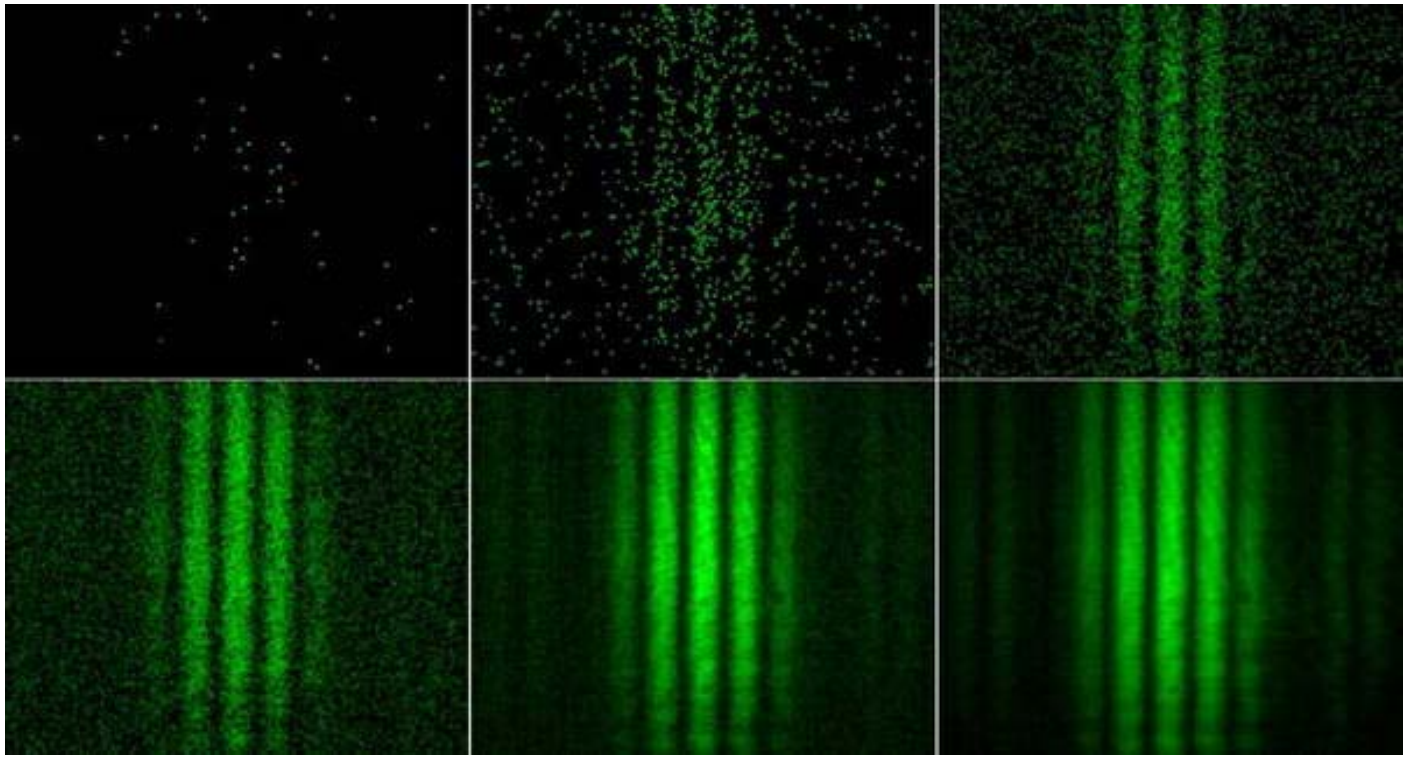


Light waves **interfere**.

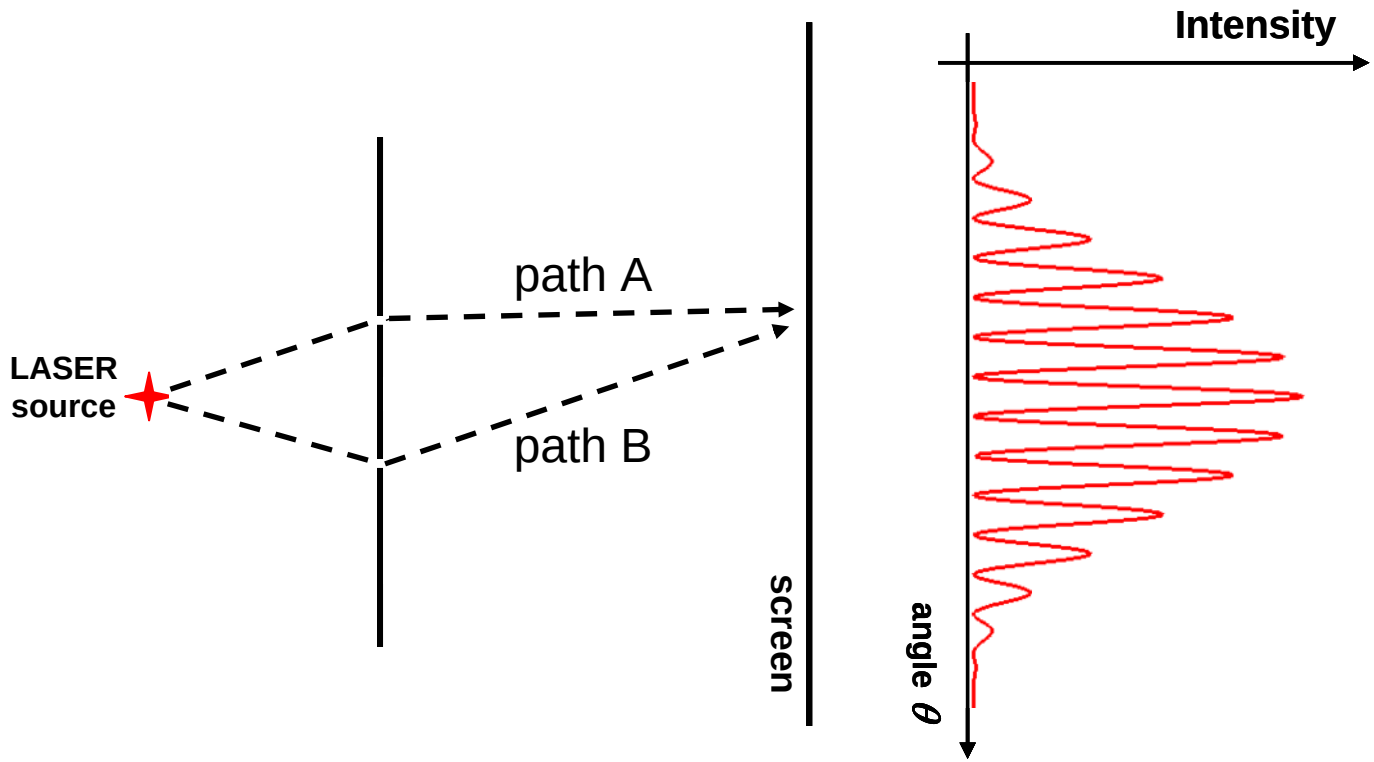
Also works for single photons !!!



[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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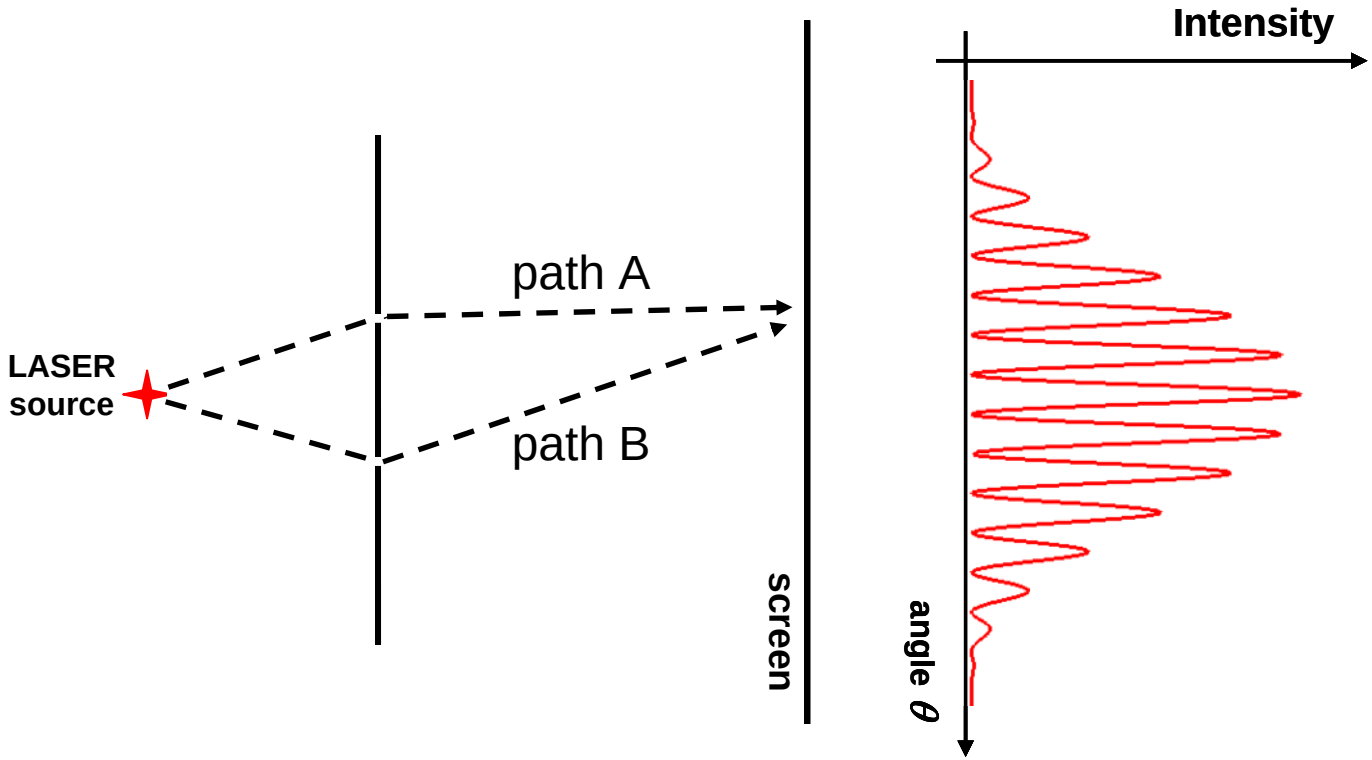
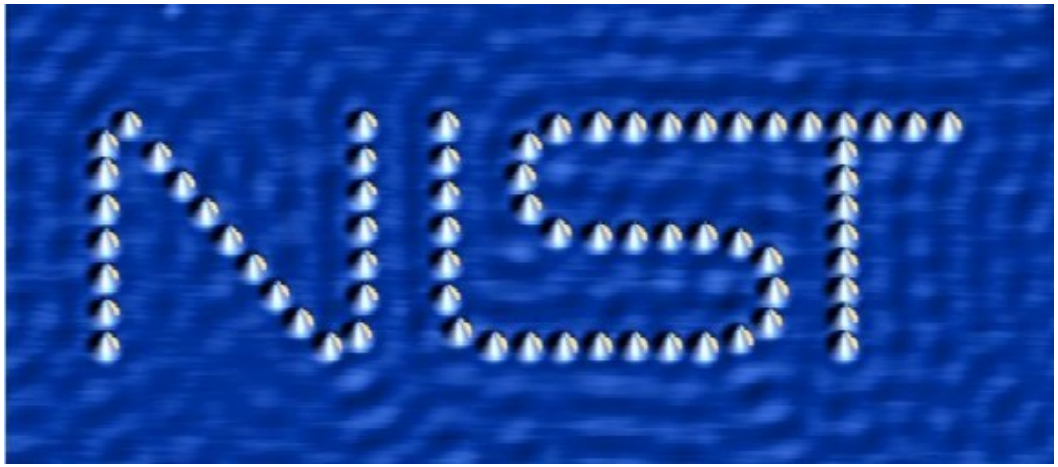
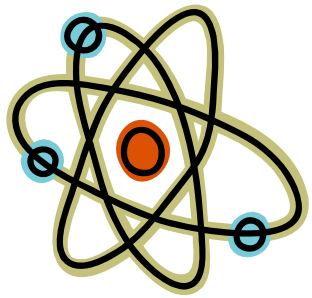


$$|\psi\rangle_{photon} = |A\rangle + e^{i\phi}|B\rangle$$

LIGHT IS A

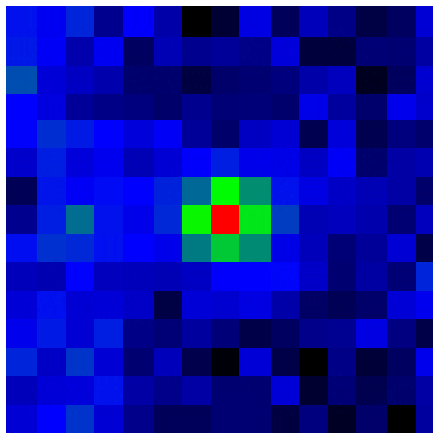
Atoms





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

[image from www.nist.gov]



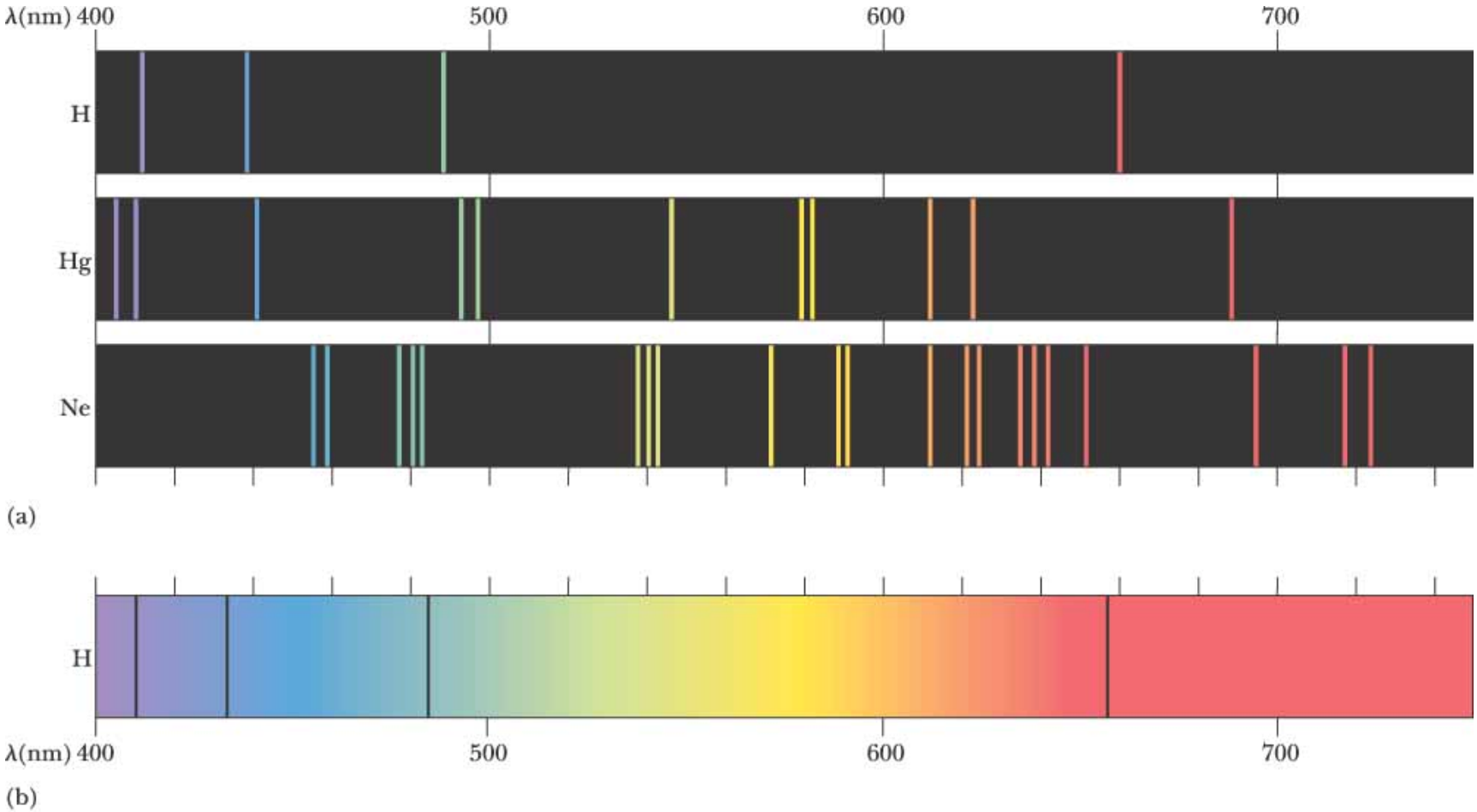
Single Rb atom
(laser cooled and trapped)

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

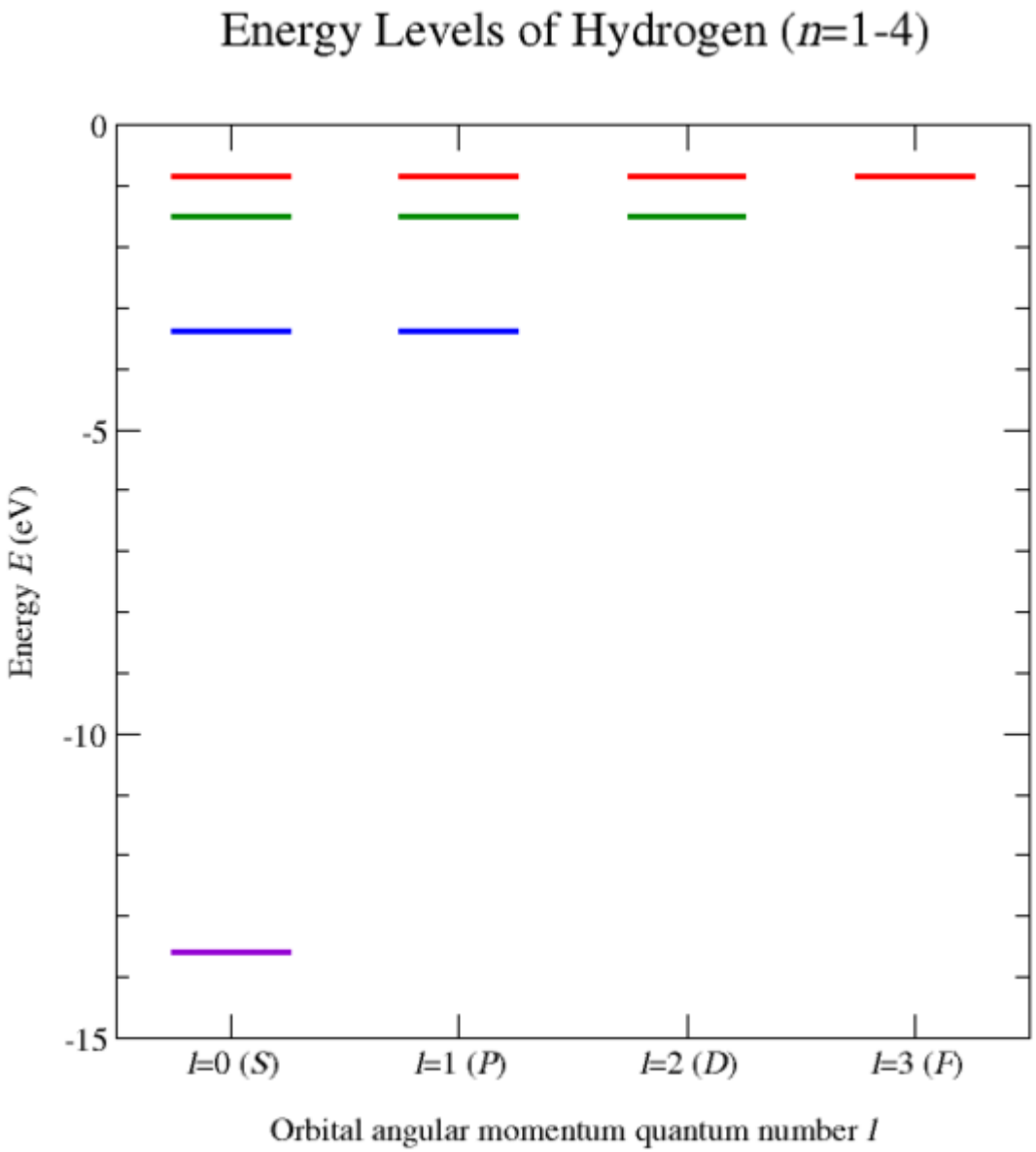
Matter is also a

How was quantum mechanics discovered?

Atomic Emission and Absorption Spectra

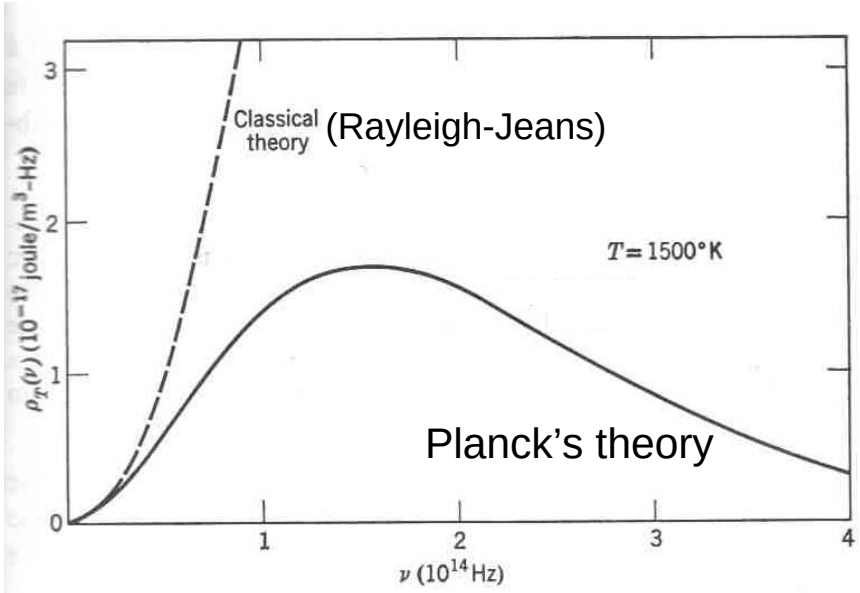


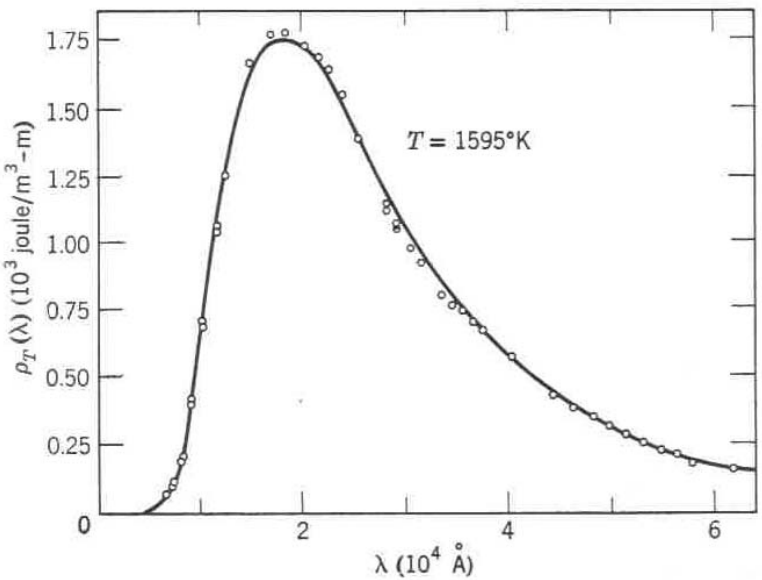
Quantum Version of Atoms



[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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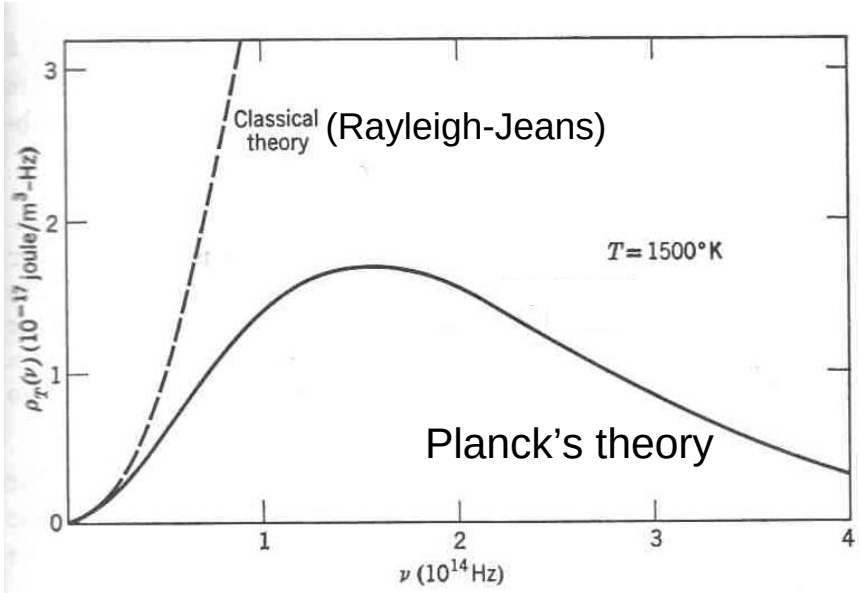
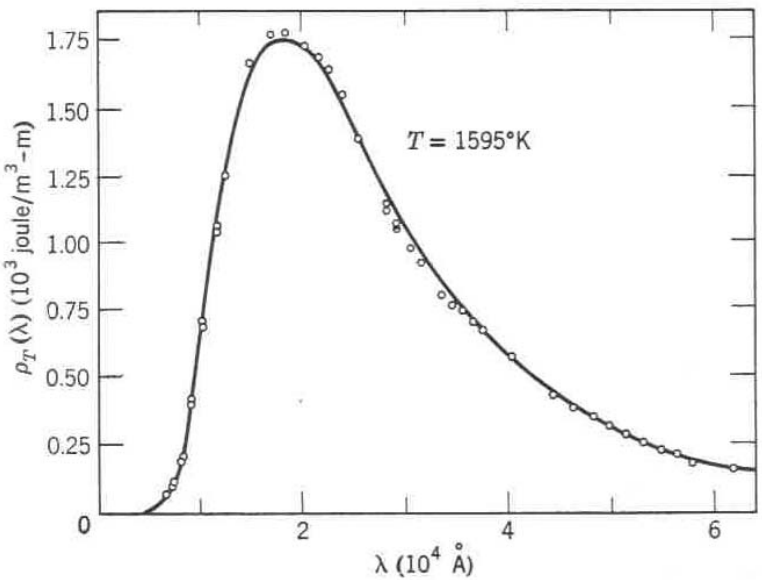


$$E = \hbar\omega$$



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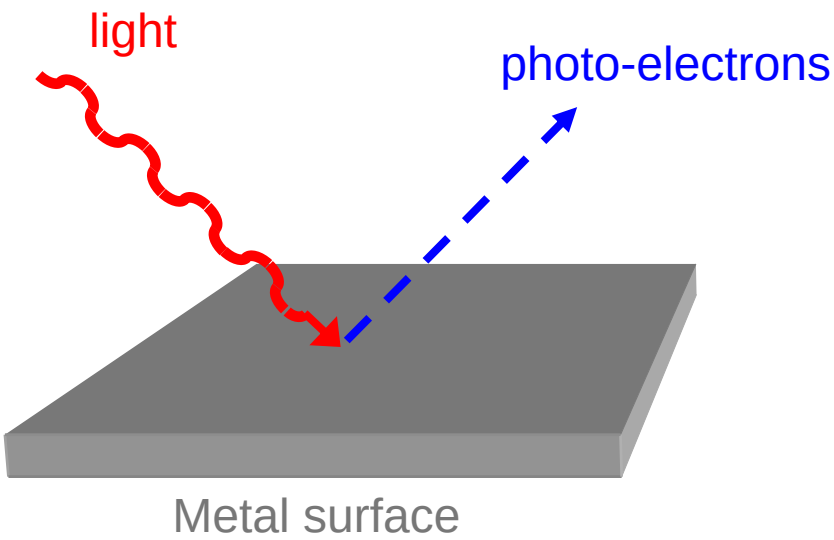

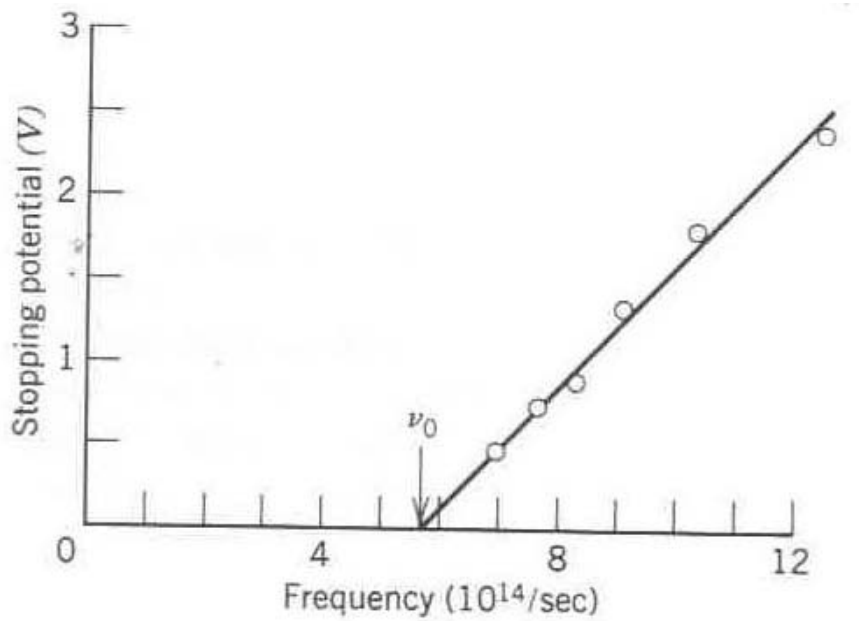

Millikan's photo-electric data for sodium (1914)

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

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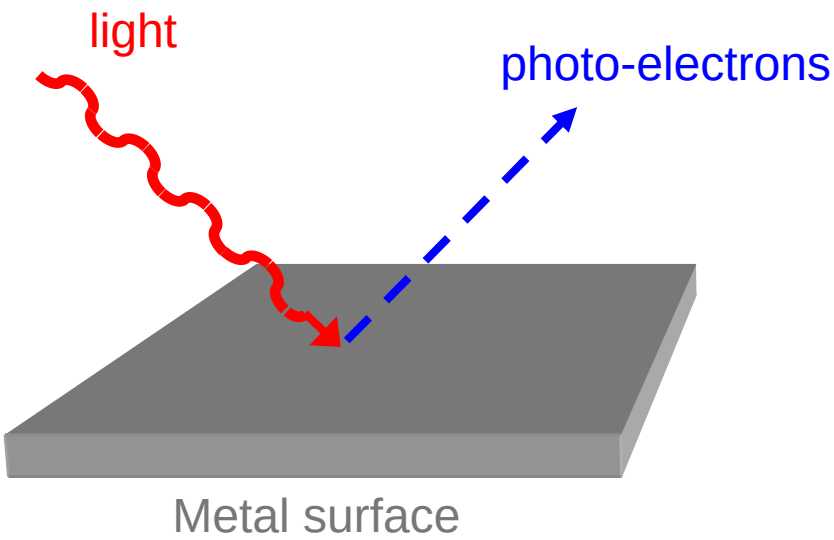

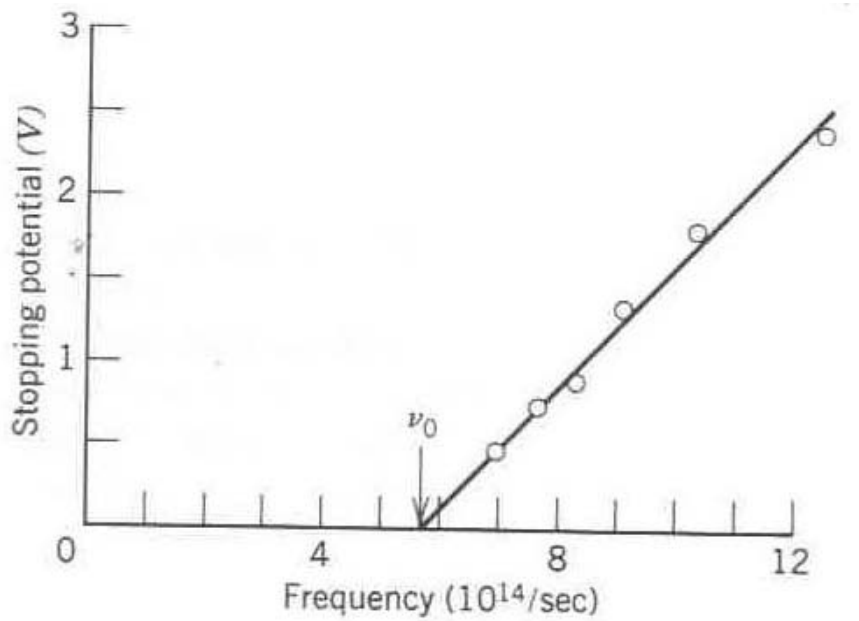

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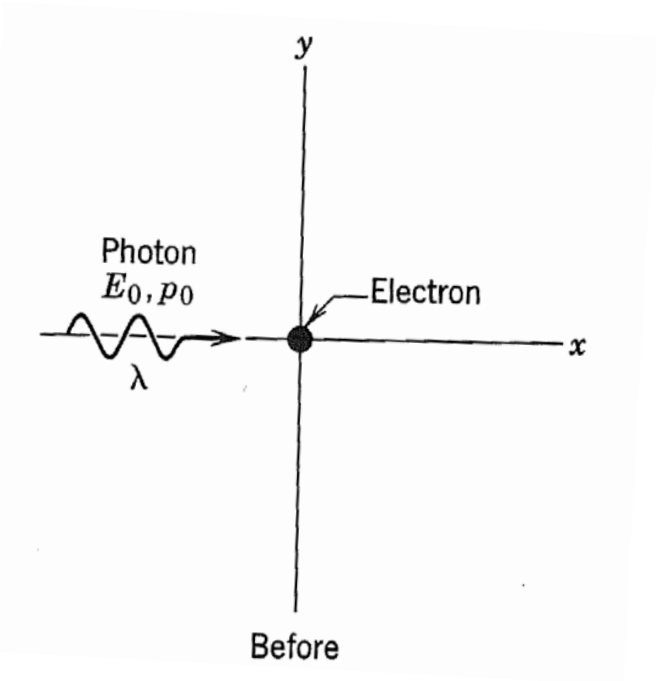
Compton Scattering



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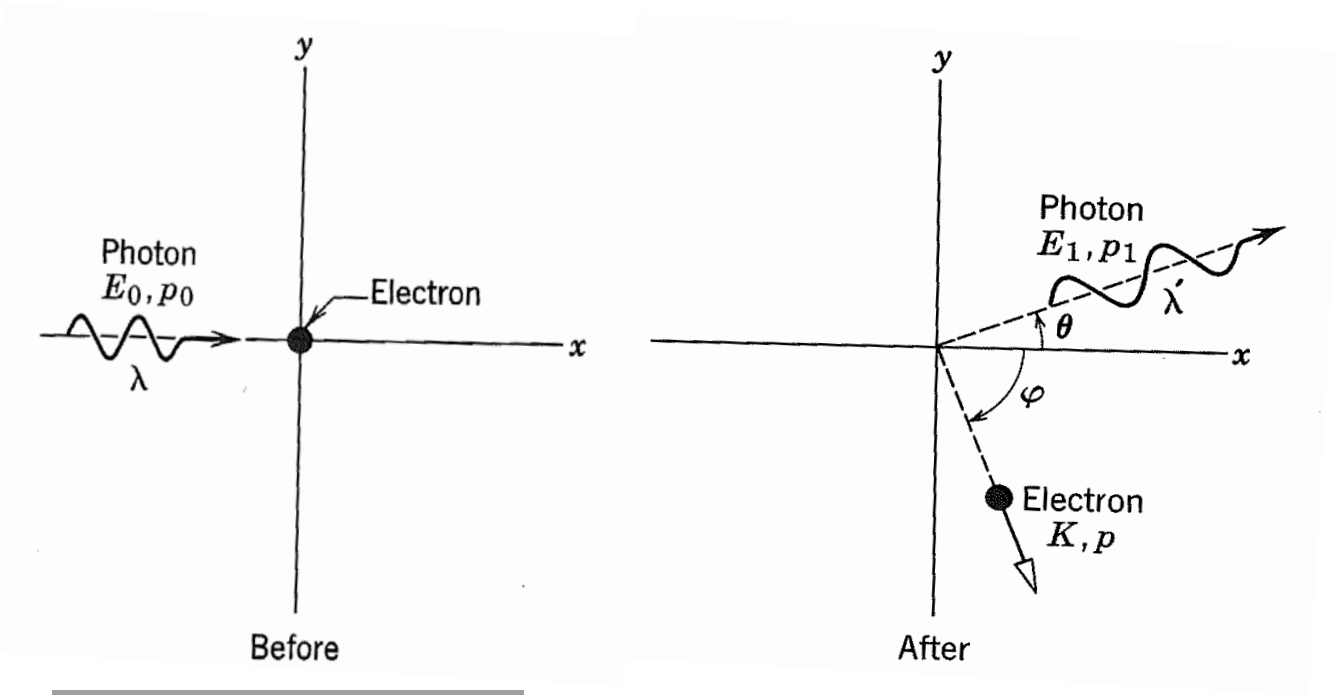

$$E = \hbar\omega$$

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

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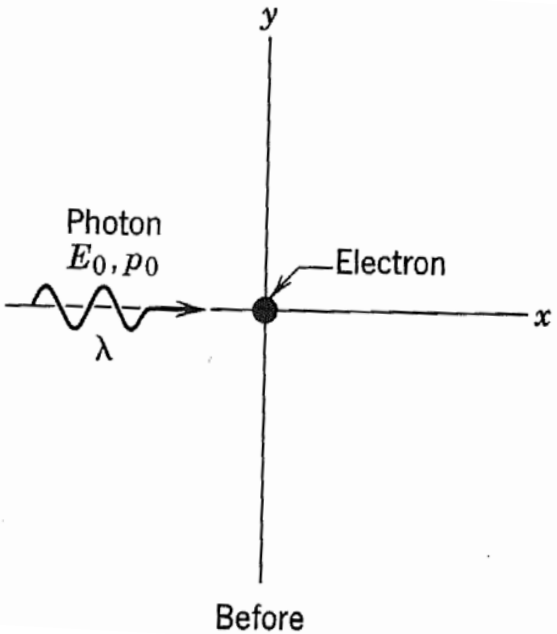

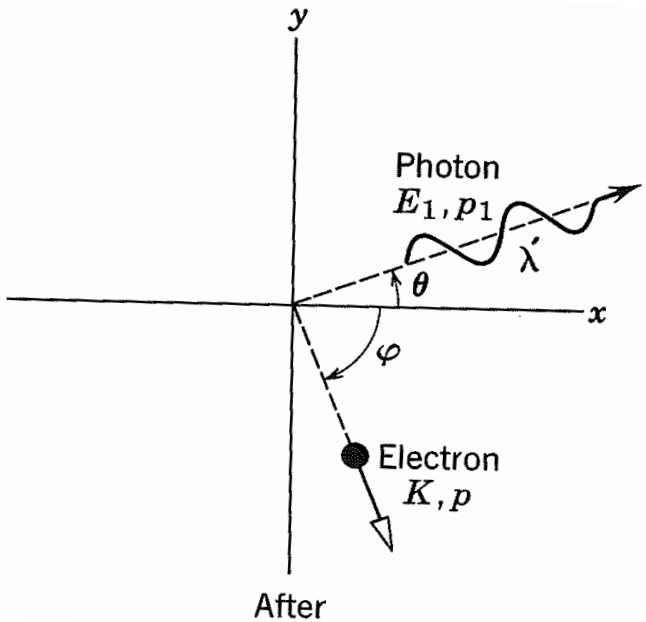

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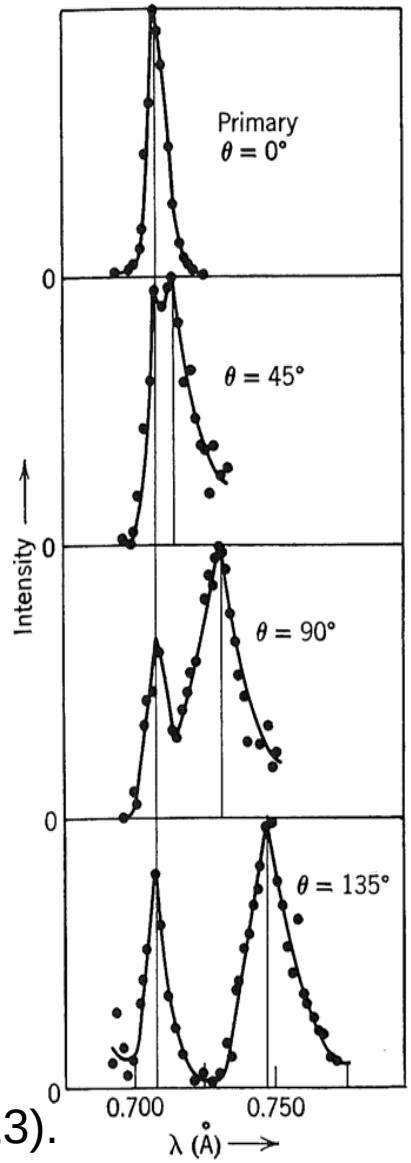

Compton's data for x-ray scattering in graphite (1923).

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

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- Essential to the discovery of Quantum Mechanics

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- 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^{14}.**
- 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.