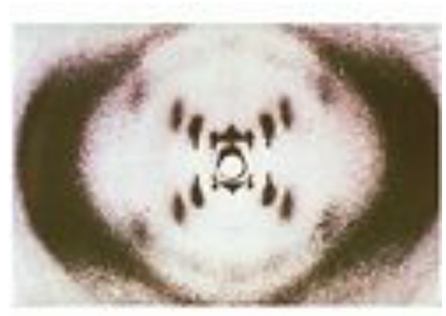
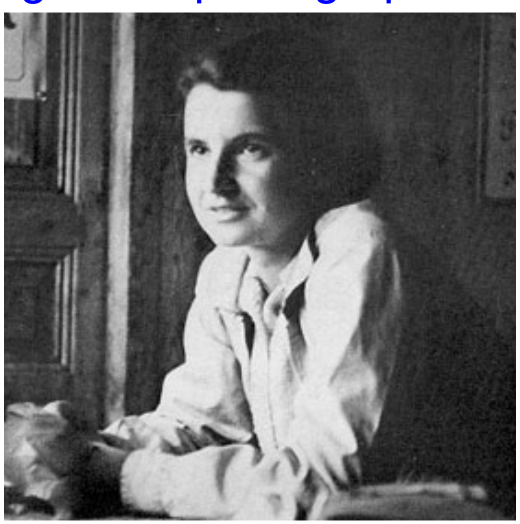
Physics 294H

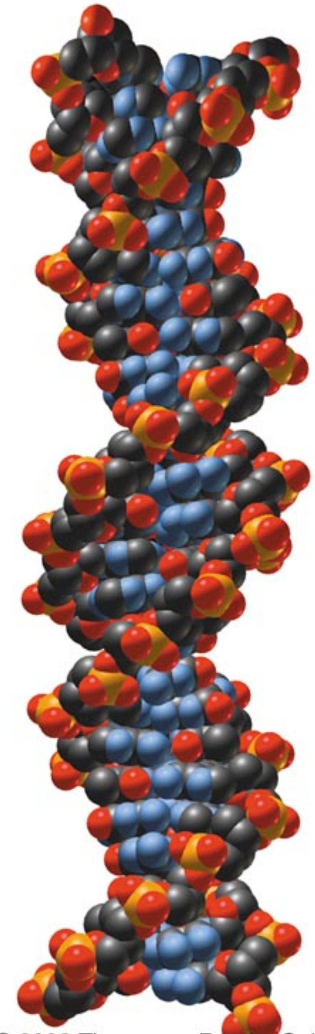
- Professor: Joey Huston
- email:huston@msu.edu
- office: BPS3230
- Homework will be with Mastering Physics (and an average of 1 hand-written problem per week)
  - **Help-room hours: 12:40-2:40 Monday (note change); 3:00-4:00 PM Friday**
- Average on 3rd exam =77/120
- I will provide a provisional grade taking into account homework + iclicker questions before the end of the week
- **Final exam Thursday May 5 10:00 AM – 12:00 PM 1420 BPS**
  - **Are there any conflicts?**
- Course website: www.pa.msu.edu/~huston/phy294h/index.html
  - lectures will be posted frequently, mostly every day if I can remember to do so

Rosalind Franklin

- "As a scientist Miss Franklin was distinguished by extreme clarity and perfection in everything she undertook. Her photographs are among the most beautiful X-ray photographs of any substance ever taken. Their excellence was the fruit of extreme care in preparation and mounting of the specimens as well as in the taking of the photographs. "







cross pattern of X-ray diffraction picture was a clue that DNA had a helical structure…a clue picked up by Watson and Crick for their Nobel prize winning work 50 years ago…which did not include Franklin

The Eagle Pub

- …which is where Watson and Crick did most of their work on the structure of DNA

James Watson and Francis Crick.

And now for something completely different: blackbody radiation

- **Blackbody radiation**
- An object at any temperature radiates thermal radiation
- Careful study of thermal radiation shows that it consists of a continuous distribution of wavelengths from infrared, visible and ultraviolet portions of spectrum
- From classical viewpoint, thermal radiation originates from accelerated charged particles near surface of object
  - those charges emit radiation like small antennas
  - charges can have distributions of accelerations, so continuous distribution of radiation

- So what's the problem?
- Problem was in understanding the observed distribution of wavelengths in radiation emitted by a *black body*

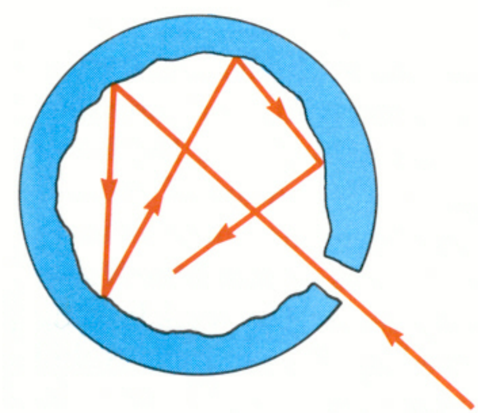
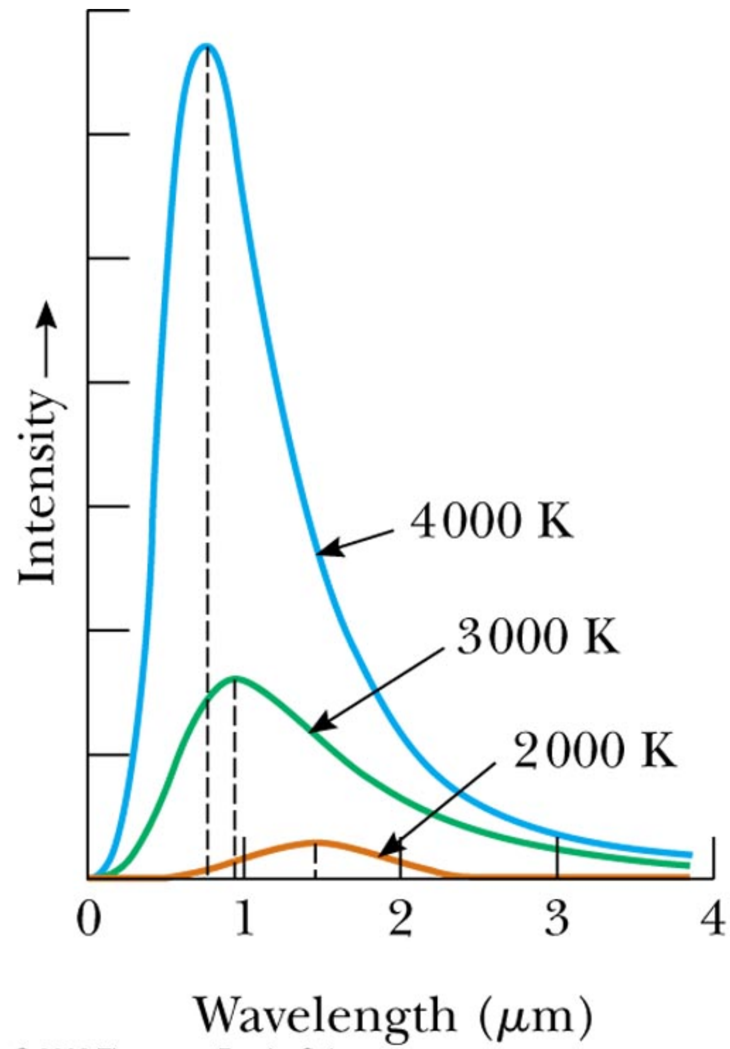


Figure 40.1 The opening in the cavity of a body is a good approximation to a blackbody. As light enters the cavity through the small opening, part is reflected and part is absorbed on each reflection from the interior walls. After many reflections, essentially all of the incident energy is absorbed.

Blackbody radiation

- Radiated energy varies with wavelength and temperature
- As temperature of blackbody increases, total amount of energy increases
- With increasing temperature, peak also shifts to shorter wavelengths
- Shift follows Wien's displacement law
  - $\lambda_{max}T=0.2898X10^{-2}$ m·K

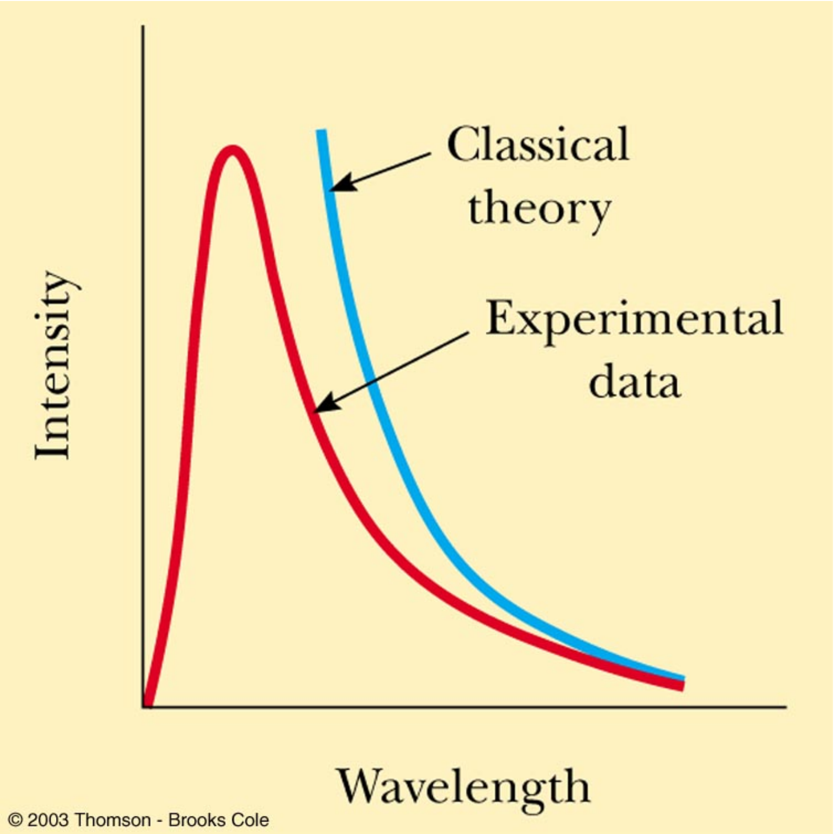


Thermal imaging

- Consider the electromagnetic radiation given off by the human body (~35^{o}C, or 308 ^{o}K)
  - λ_{max} = 0.2898X10^{-2} m.^{o}K / 308 ^{o}K = 940 μm
  - far infra-red

Ultraviolet catastrophe

- Attempts to describe results based on classical theory didn't work
- Rayleigh-Jeans law
  - $I(\lambda,T)=2\pi ckT/\lambda^4$
  - k is Boltzmann's constant, λ is the wavelength, T is the temperature
- Agreement looks ok at higher wavelengths
- As λ approaches 0, the intensity goes to infinity
- Oops
- The ***ultraviolet catastrophe***



Max Planck comes to the rescue

- In 1900, Max Planck discovered a formula for blackbody radiation in complete agreement with experiment at all wavelengths
  - $I(\lambda,T) = \dfrac{2\pi hc^2}{\lambda^5(e^{hc/kT} - 1)}$
  - where h is a constant that can be adjusted to fit the data
  - h (Planck's constant) =6.626X 10^{-34} J.s
    - …remember, we came across this *h* before, when we talked about the energy in light (E=hf)
  - agrees with Rayleigh-Jean law at higher wavelength

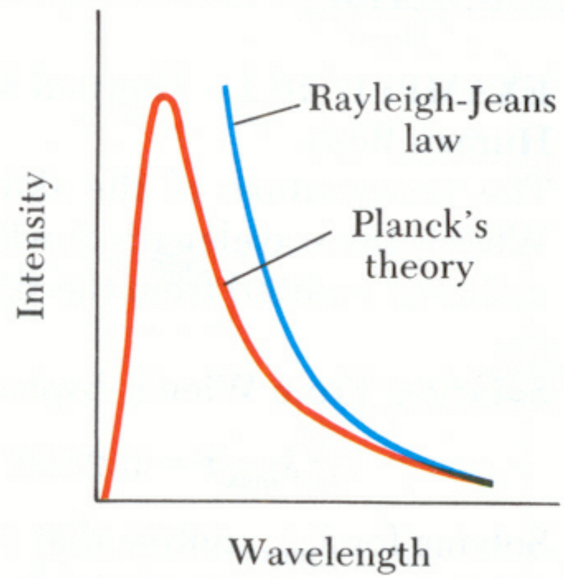


Figure 40.3 Comparison between Planck's theory and classical theory for the distribution of blackbody radiation.

…so how did he do it?

- Consider molecules in interior of black body as oscillators
- Planck made 2 bold assumptions regarding these oscillators
  - oscillating molecules that emit the radiation could only have discrete units of energy E_n given by
    - $E_n=nhf$
    - n is integer and f is frequency
  - molecules can emit or absorb energy in discrete units called quanta or photons
    - they do so by jumping from one quantum state to another
- Key point is the assumption of **quantized energy states**; this marked the birth of quantum theory

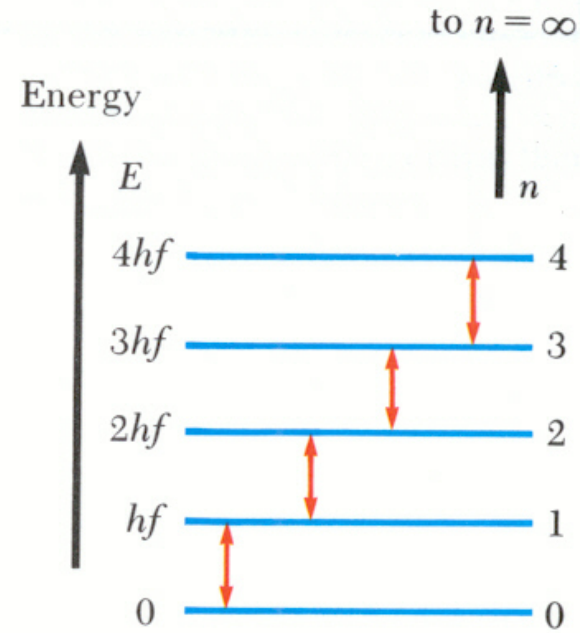
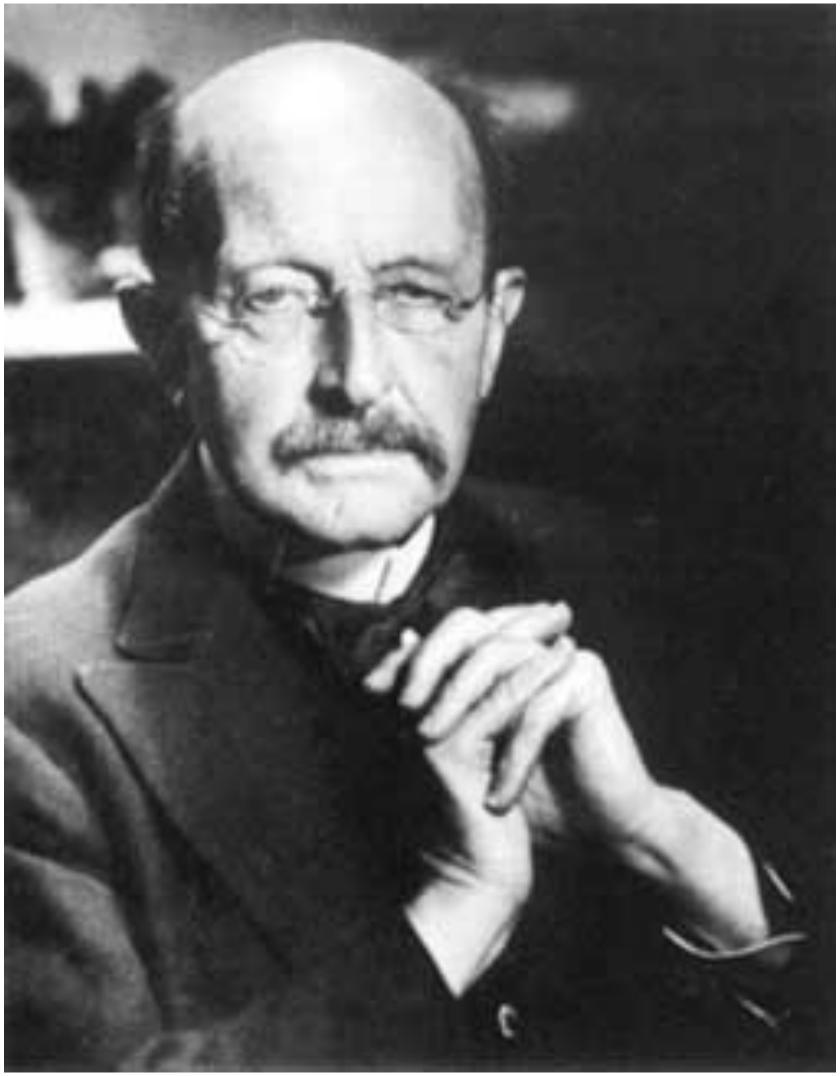


Figure 40.4 Allowed energy levels for an oscillator of natural frequency f. Allowed transitions are indicated by vertical arrows.

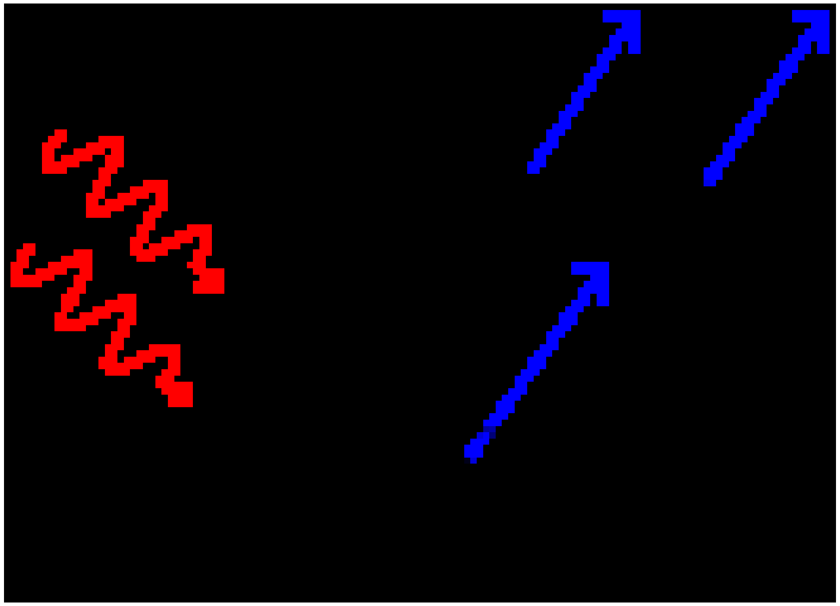
It wasn't easy to establish a new paradigm

- It took Planck 6 years of work.
  - "I tried immediately to weld the elementary quantum of action somehow in the framework of classical theory. But in the face of all such attempts this constant showed itself to be obdurate ... My futile attempts to put the elementary quantum of action into the classical theory continued for a number of years and they cost me a great deal of effort. "



Photoelectric effect

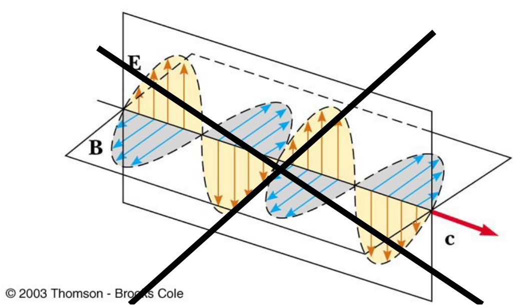
- The **photoelectric effect** is a quantum electronic phenomenon in which electrons are emitted from matter after the absorption of energy from electromagnetic radiation such as x-rays or visible light. The emitted electrons can be referred to as *photoelectrons* in this context. The effect is also termed the **Hertz Effect**, due to its discovery by Heinrich Rudolf Hertz, although the term has generally fallen out of use.Study of the photoelectric effect led to important steps in understanding the quantum nature of light and electrons and influenced the formation of the concept of wave–particle duality.

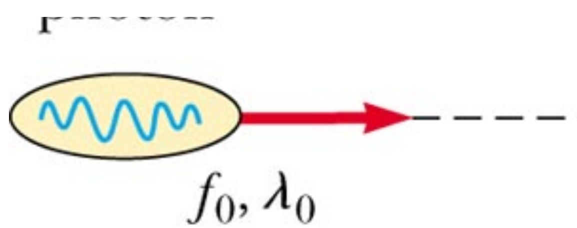


Whether electrons were emitted didn't matter on the intensity of the light, just on its wavelength.

Einstein was a busy guy in 1905

- Einstein extended Planck's concept of quantization to electromagnetic waves
- He assumed that light of frequency f can be considered as a stream of photons with each photon having an energy given by **E=hf**, where h is Planck's constant
- Energy of light is not distributed evenly over classical wavefront, but instead is concentrated in bundles or energy called photons
- For the photoelectric effect, It doesn't matter how many photons you have, only their energy



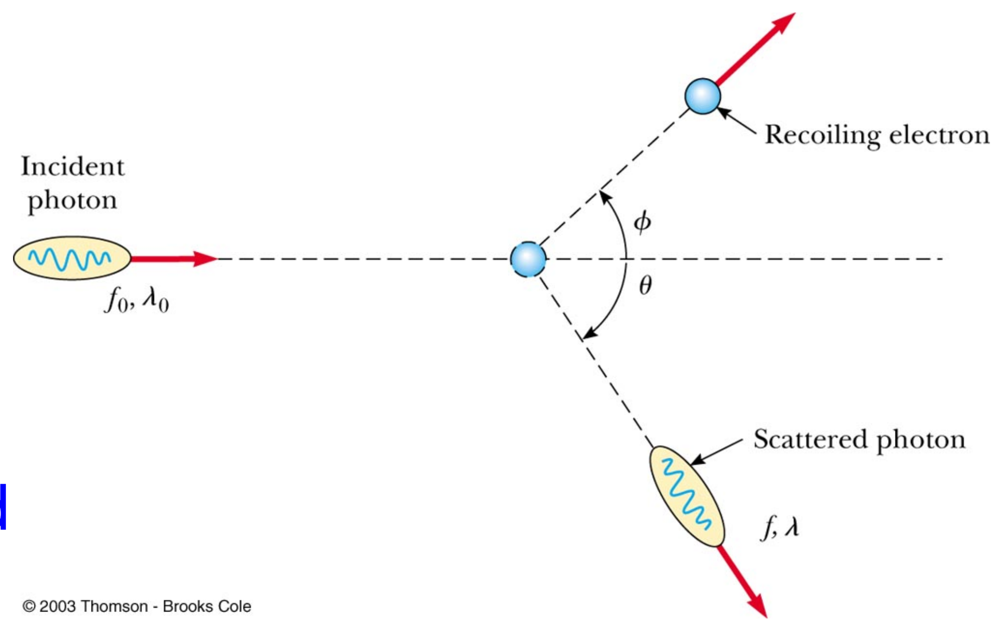


Compton Effect

- More evidence for the photon nature of light
- Arthur Compton directed an X-ray beam of wavelength λ_o towards a block of graphite and found that the scattered X-rays had a slightly longer λ than the incident X-rays
- Longer λ means lower energies
- Change in wavelength is called the Compton shift

Compton's model

- X-ray photon carries both energy and momentum
- Its collision with an electron is like the collision of two billiard balls
- The photon transfers some of its energy and momentum to the (stationary) electron and so its energy is smaller and its wavelength is longer by an amount
  - $\Delta\lambda = \lambda - \lambda_o = h/(m_e c)\,(1-\cos\theta)$
  - $h/(m_e c)$ is called the Compton wavelength = 0.00243 nm



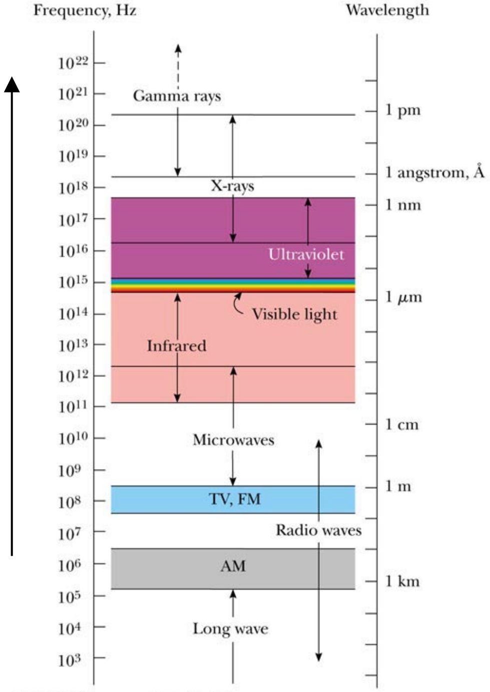
shift is very small so only noticeable for small wavelength radiation, i.e. X-rays

Particle nature of light

- Light has a particle nature as well as a wave nature
- The concept of the photon was introduced by Albert Einstein to explain the photoelectric effect
- Photon model
  - light consists of discrete massless units called photons
  - each photon has energy E=hf
    - h=Planck’s constant=6.63X10^{-34} Js
  - the superposition of a sufficiently large number of photons has characteristics of classical light wave

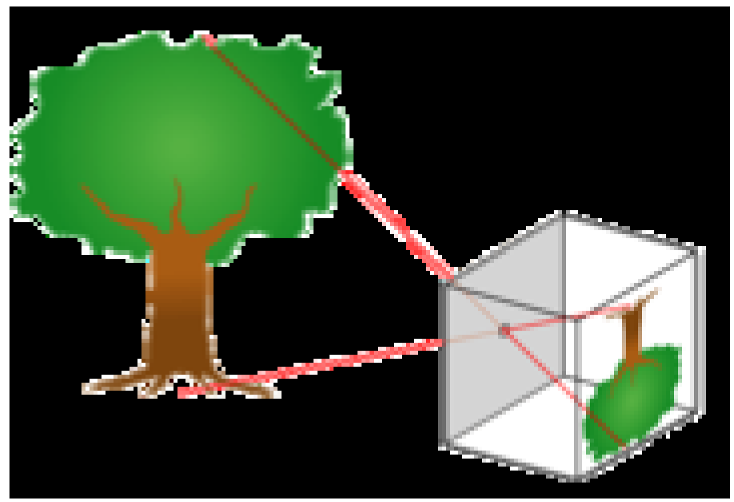
…as with photon torpedoes

increasing E



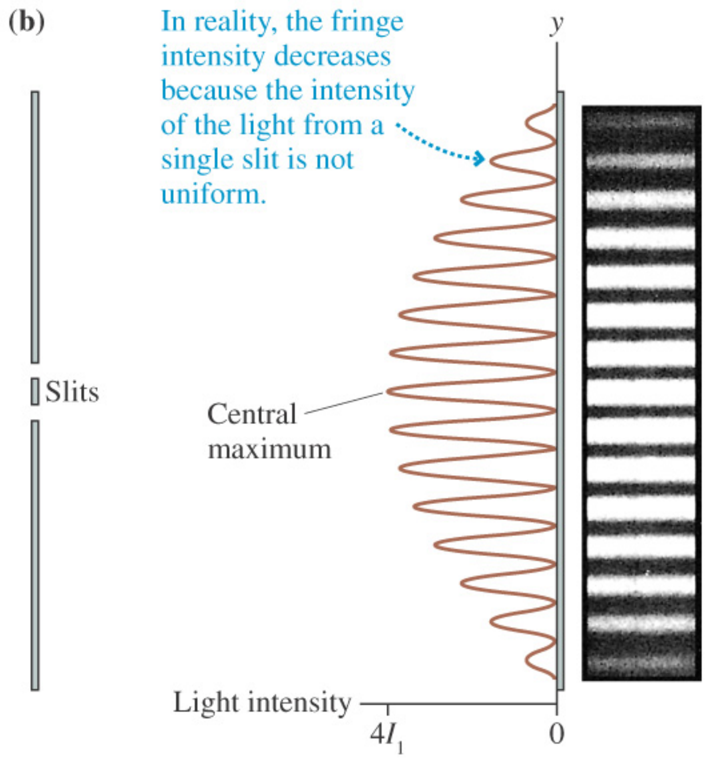
Aside: Pinhole camera and photons

- You don’t need a lens to make a camera
- Can make a simple camera by having a pinhole which light can come through only at a specific angle
- But long exposure times needed since basically only 1 photon at a time hits the film

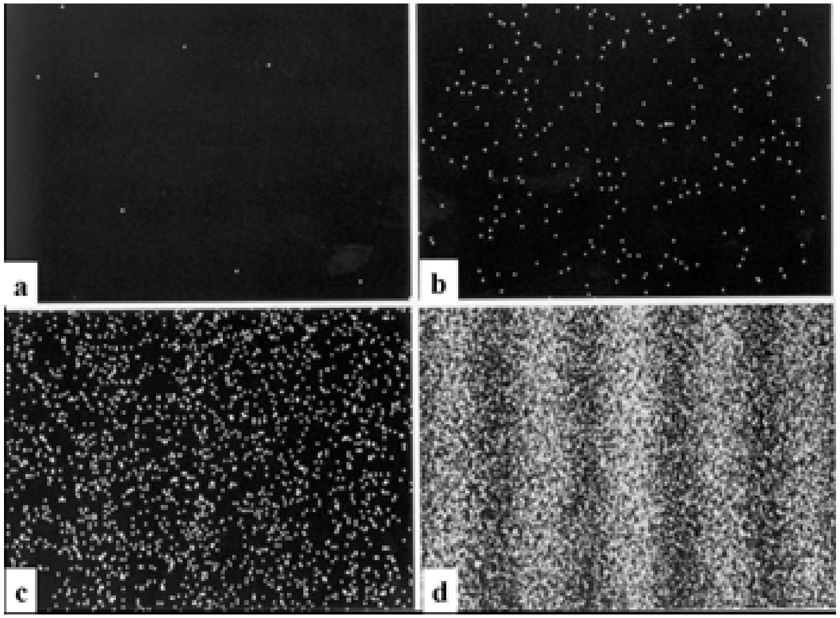


Revisit the double slit experiment

- We talked about a plane EM wave entering both slits
- The wave diffracts through both slits and the diffracted waves then interfere with each

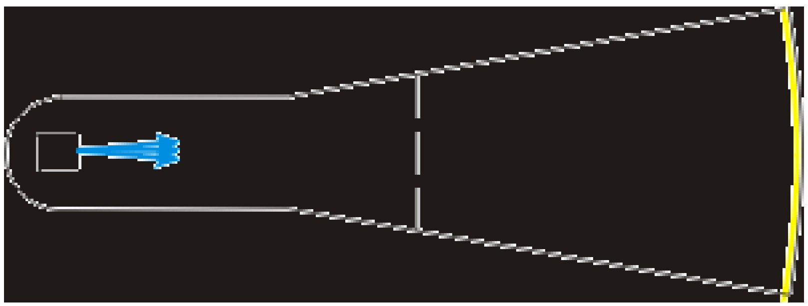


Suppose the light intensity is so low that only a quantum of light (a photon) passes through either one slit or the other at a time. What does the pattern look like on the screen?



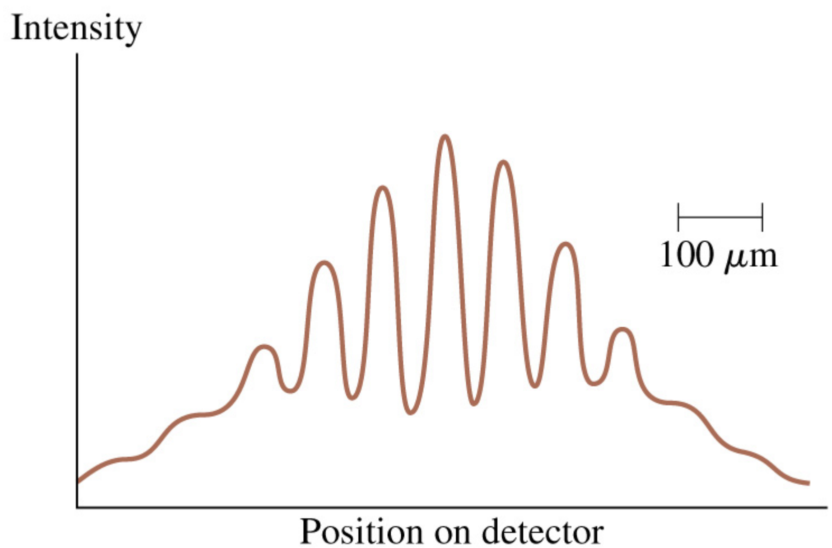
Matter waves

- Suppose we re-do the double-slit experiment but now fire electrons through a double-slit system at the screen
- What do we see?



- We see that the electron beam shows signs of
  - diffraction
  - interference
- i.e. something that we normally think of as a particle can also behave as a wave

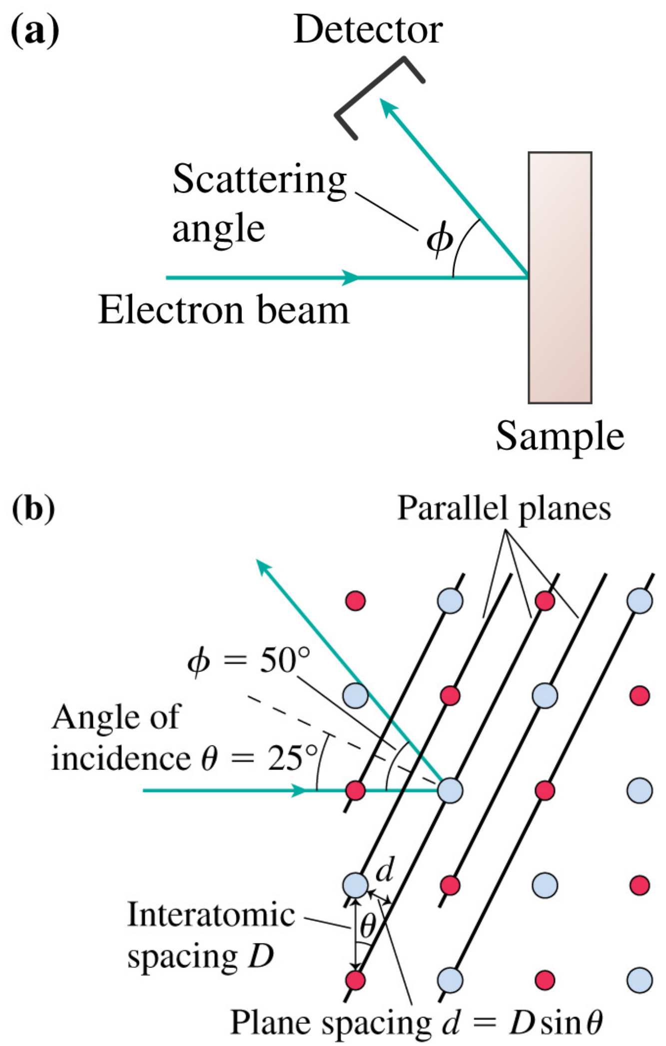
(b) Double-slit interference of neutrons



ActivePhysics

Davisson and Germer

- In 1927, they were carrying out an experiment at Bell Labs looking how electrons scatter from the surface of a metal
- The intensity pattern they saw had minima and maxima just like if they were scattering X-rays of wavelength < 1 nm



(Prince) Louis de Broglie

- His reasoning in 1924
  - suppose I have a particle with momentum p
  - it has a kinetic energy, $E=p^2/2m$
  - if it has a wavelike property as well, then I should be able to write
    - $E=hf=hc/\lambda$
  - I can ascribe a wavelength to a a particle
    - $\lambda=h/p$
    - there's Planck's constant again
    - wavelengths involved are small, so wave nature of particles usually shows up only at atomic level

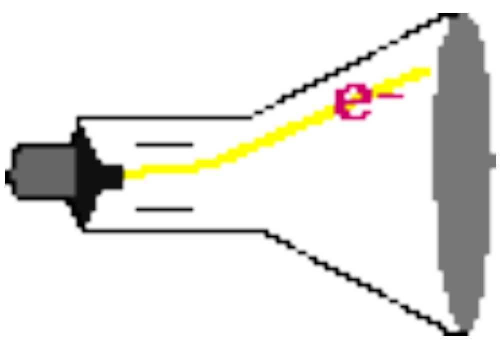
(Prince) Frederick Lobkowicz

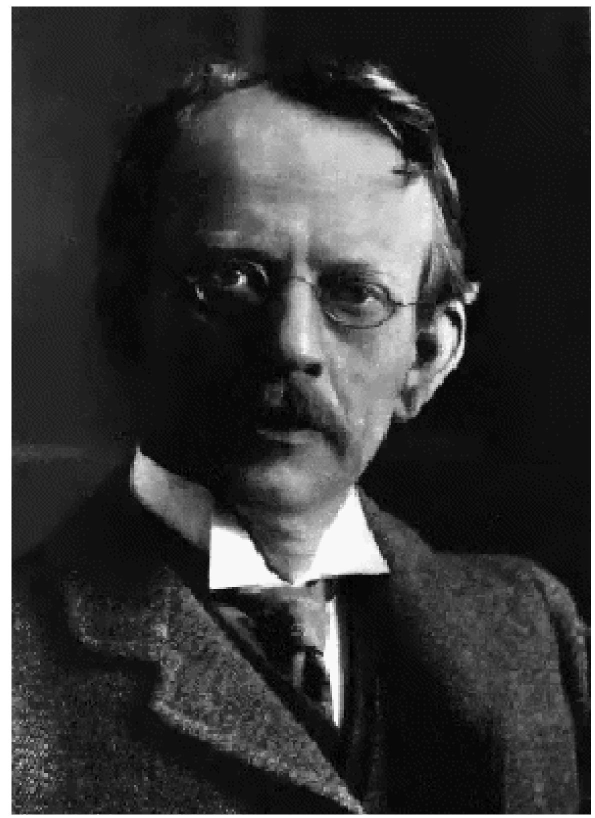
- My thesis advisor

View of Lobkowicz family castle of Nelahozeves by Carl Croll, 1841

Backtrack: atoms are not fundamental

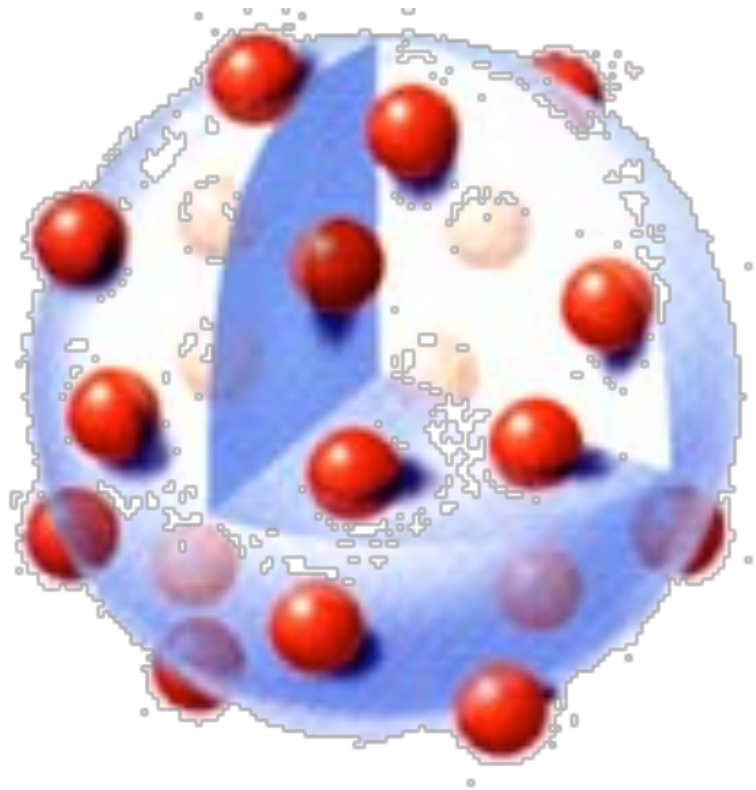
- Enter JJ Thomson
- In late 1890s, JJ did experiments using cathode ray tubes.
- By 1895, he had discovered *electrons* were coming from atoms.





Plum Pudding Anyone?

- This led JJ to think of the atom as a positively charged mass sprinkled with negative electrons.
- These electrons seemed identical from different atoms
- Thus electrons seemed to be a fundamental piece of matter.



Einstein

- After Einstein's Famous series of papers in 1905, physicists managed to combine the once seemingly different electric & magnetic forces into one.
- In addition, the light particle-photon seemed to play an important role.

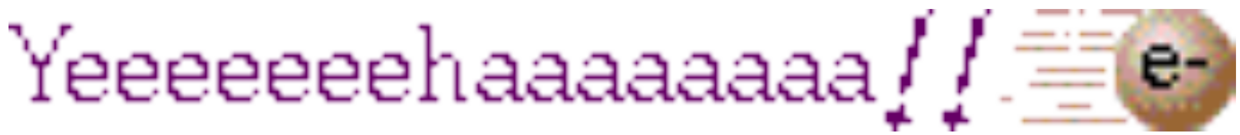
But the Atom is Not Stable

- Many researchers started to work with radioactive elements.
- A typical technique was to bombard some materials with radioactive particles.
- The New Zealander Rutherford was a leader in this type of research.

Quickie Reminder

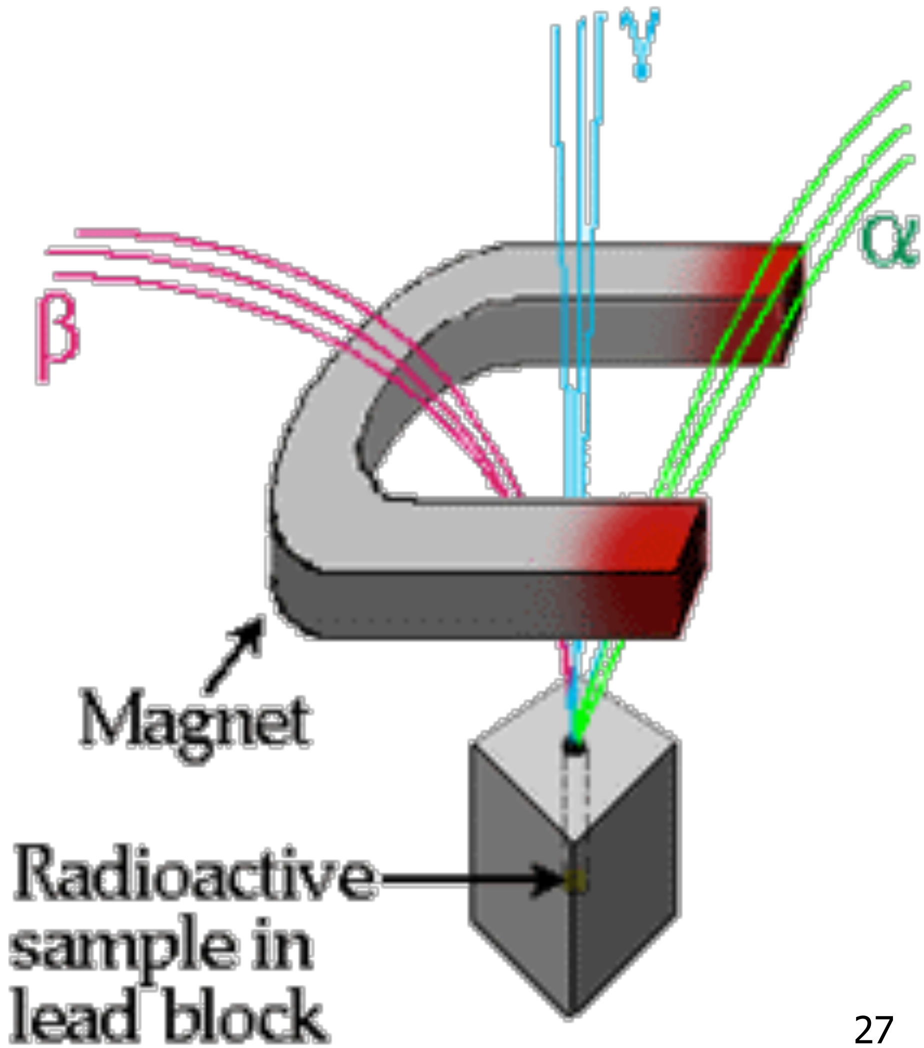
- Alpha particles are helium nuclei (2 p, 2 n):

- Beta particles are speedy electrons:

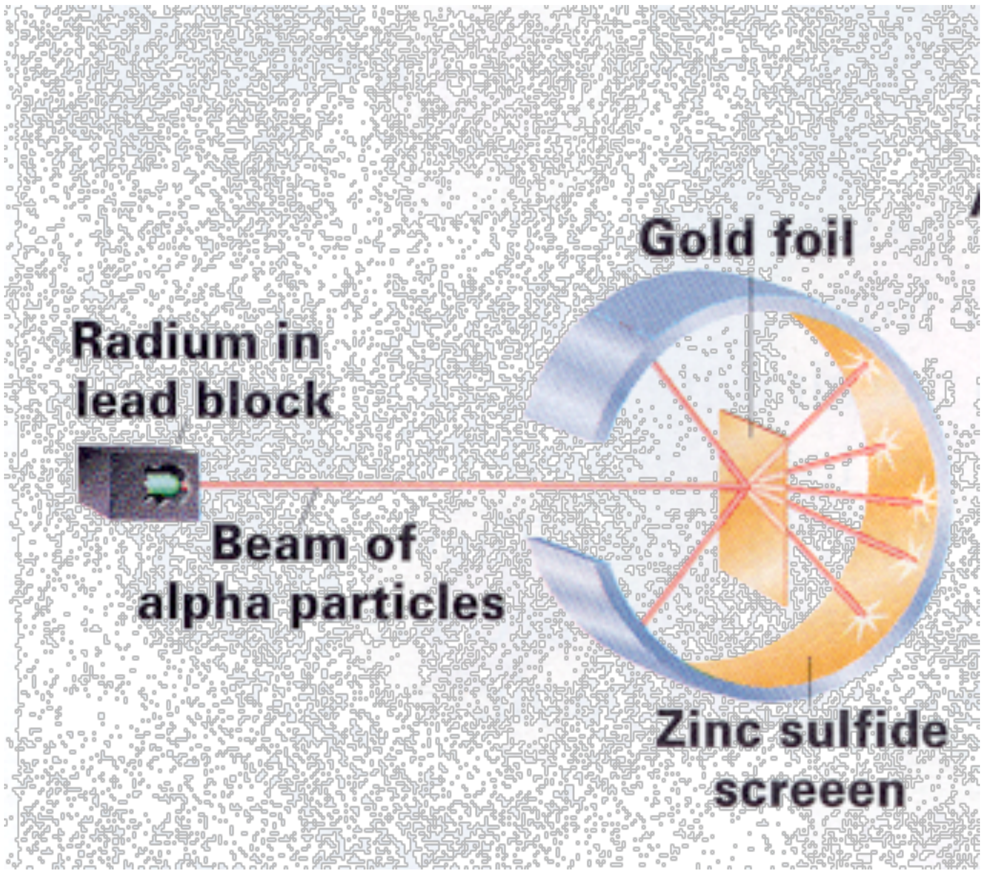


- Gamma radiation is a stream of photons:

Simple Detecting

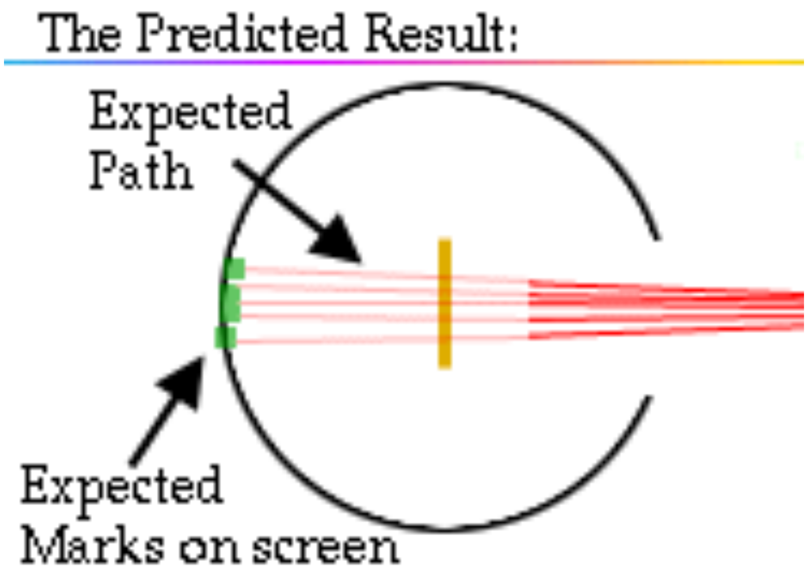


Enter the Students

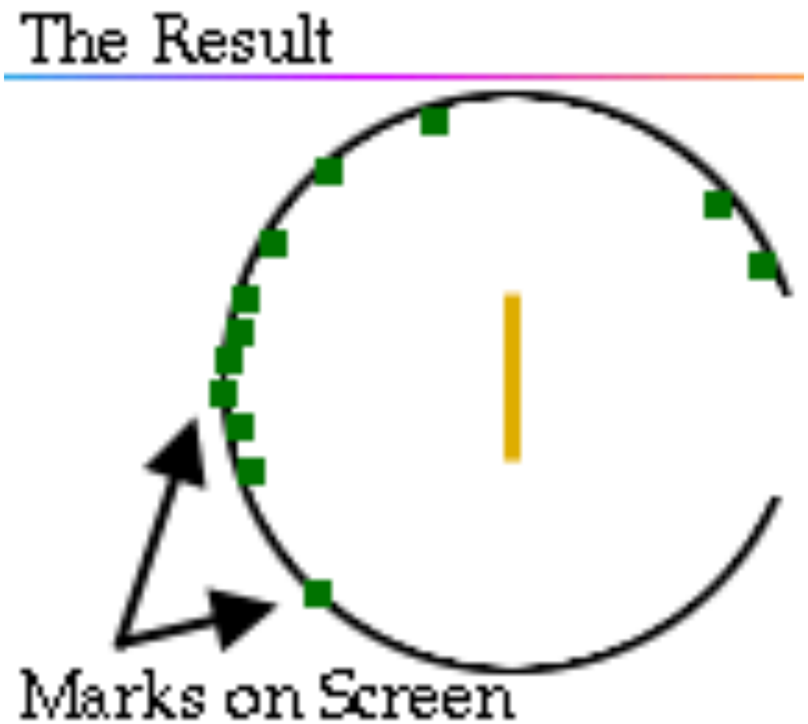


- Rutherford had two grad students, Marsden and Geiger.
- It was decided that Geiger would gain some practice by conducting a series of experiments with gold and alpha particles.

- On the screen, marks were only expected to appear in a limited region.
- Geiger was to explore the places where no results were anticipated.

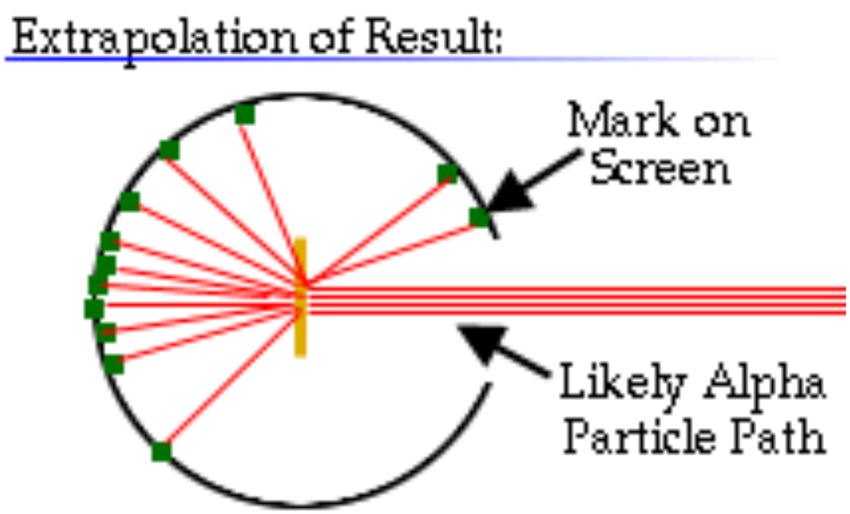


Instead…



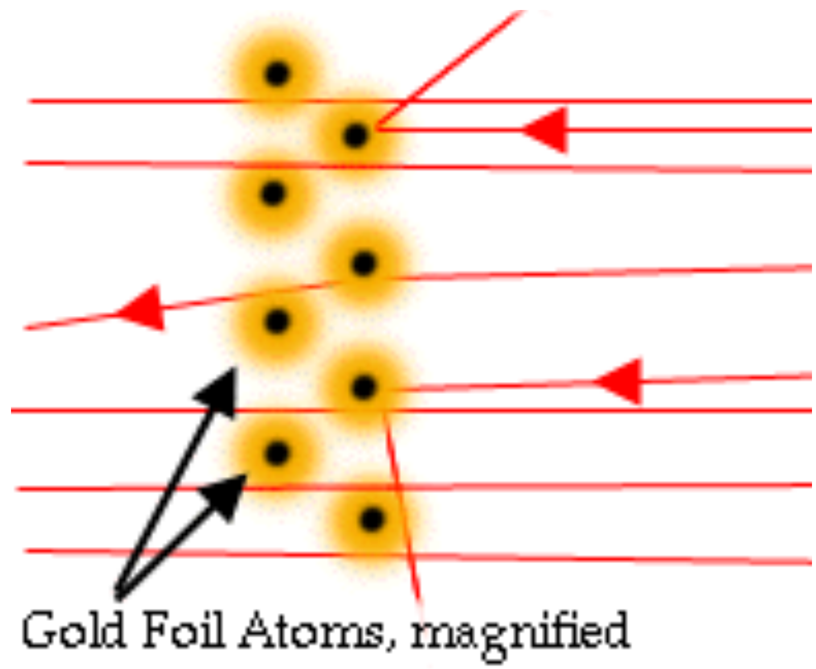
- Marsden had to excitedly tell Rutherford that the new student had actually gotten results!
- Some were almost straight back!

- Rutherford would later compare it to firing a cannonball at a piece of tissue paper and having the ball bounce back!



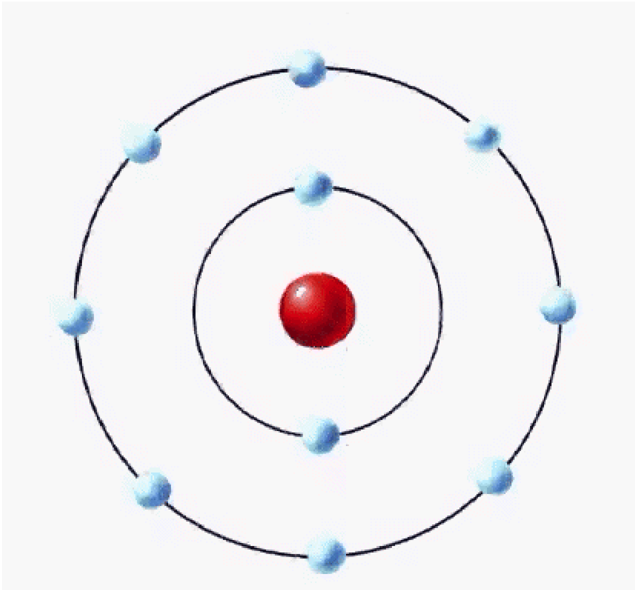
Positive Nucleus

- Rutherford quickly realized that a small, very dense and positively charged nucleus would account for the paths of the alpha particles.
- It took a lot of geometry and statistics to eventually convince other physicists and to show how big the nucleus was.



“Solar System Model”

- This led to the classic model of the atom- similar to the solar system
- Distant electrons orbit a massive nucleus due to electrical forces of attraction.



Big Problems.

- Rutherford's model was very appealing but there were some "minor" problems that had to be solved.
- What held the nucleus together to be so small?

  AND…
- The orbiting electrons were giving off light, due to Conservation of Energy, they should eventually spiral into nucleus!