

# Dr. Quantum

## Dr. Quantum Explains

<http://www.youtube.com/watch?v=DfPeprQ7oGc>



# Photons (25.3)

The photo at very low light levels shows individual points, as if particles are arriving at the detector.



The particle-like behavior is not noticeable at higher light levels.

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- The picture above is more astounding than it looks.
- If light was a wave, then taking a photo in very low light should produce a very dim version of the whole image. As the luminosity increases, we should see the photo get brighter.

# Photons (25.3)

The photo at very low light levels shows individual points, as if particles are arriving at the detector.



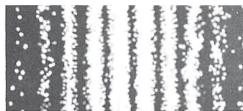
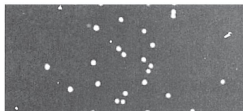
The particle-like behavior is not noticeable at higher light levels.

Increasing light intensity

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- Acckkkk!!! We instead see the photo accumulate one dot at a time. As if light were a stream of particles and we were merely controlling the flow-rate.
- How do we reconcile this with our models of light??

# Double-Slit Interference Revisited



The particle-like dots arrange themselves into wave-like interference fringes.

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- The double-slit experiment showed us that light is definitely wave-like....or is it?
- If we again go to the low intensity limit we should see dim versions of each of the constructive fringes.
- Instead we see the dots appearing on the screen one at a time. Eventually they form an interference pattern, but the hit like particles, not like a wave.
- So, they make a pattern like a wave despite interacting as particles.

# The Photon Model of Light

- The basic particle of light is called a **photon**
- A photon is discrete and massless and travels at speed  $c$  in a vacuum.
- Each photon has an energy

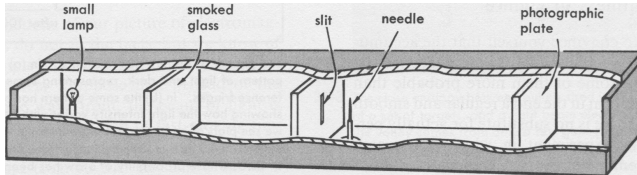
$$E_{\text{photon}} = hf$$

where  $f$  is the frequency of the light and  $h$  is **Planck's constant**

$$h = 6.63 \times 10^{-34} \text{ J} \cdot \text{s}$$

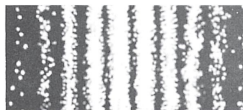
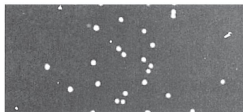
- The superposition of a large number of photons looks like a classical light wave. These are not your “classical” corpuscles.

# The Photon Model of Light



- In 1909 the English physicist G. I. Taylor did an interference experiment with a small gas lamp in a box with a slit and a small needle. A smoked glass was used to reduce the light intensity.
- The light made interference patterns on the photograph.
- He reduced the intensity of the light and increased the exposure time repeatedly.
- Eventually the light was so dim that it took 3 months to get the pattern on the film. (He went sailing during the exposure.)
- He could prove that at this low light level there was never more than a single photon in the box at a time. Nevertheless, an interference pattern was produced!

# The Photon Model of Light

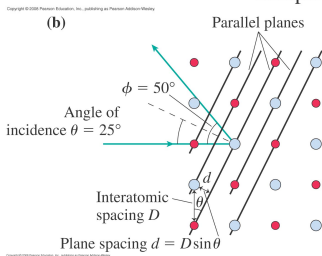
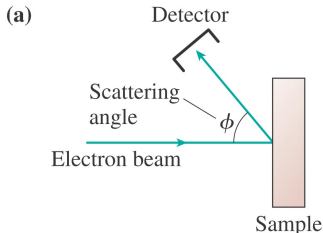


The particle-like dots arrange themselves into wave-like interference fringes.

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- Imagine doing the double slit experiment with light of such low intensity that only one photon passed through the slits at a time.
- If only one photon travels to the slits, it must pass through one or the other right?
- Wrong! The photons hit the screen one at a time and slowly build-up the “usual” interference pattern. Each photon “feels” the interference.
- Each photon travels through both slits....not at all like a particle.

# Matter Waves (25.4)



- In 1927 Davisson and Germer studied electron-scattering.
- They scattered off of a piece of nickel and saw a set of minima and maxima which reminded them of X-ray scattering!!
- They applied the equations from Bragg scattering to one of their peaks using the known atomic spacing for nickel and derived the “wavelength” of the electrons

$$\lambda = D \sin(2\theta) = 0.165 \text{ nm}$$

- They could then use this “wavelength” to predict the position of all the other peaks...just as though they were scattering X-rays!!



# The de Broglie Wavelength

- A graduate student named de Broglie had predicted this!
- Einstein (1905) had shown that the energy of a photon is:

$$E_{\text{photon}} = hf = \frac{hc}{\lambda}$$

- de Broglie wondered if matter obeyed the same sort of relationship between energy and frequency. But how do you define the “frequency” of matter?
- He knew the kinetic energy of a particle was (classically)

$$E = \frac{1}{2}mv^2 = \frac{1}{2}m\left(\frac{p}{m}\right)^2 = \frac{p^2}{2m}$$

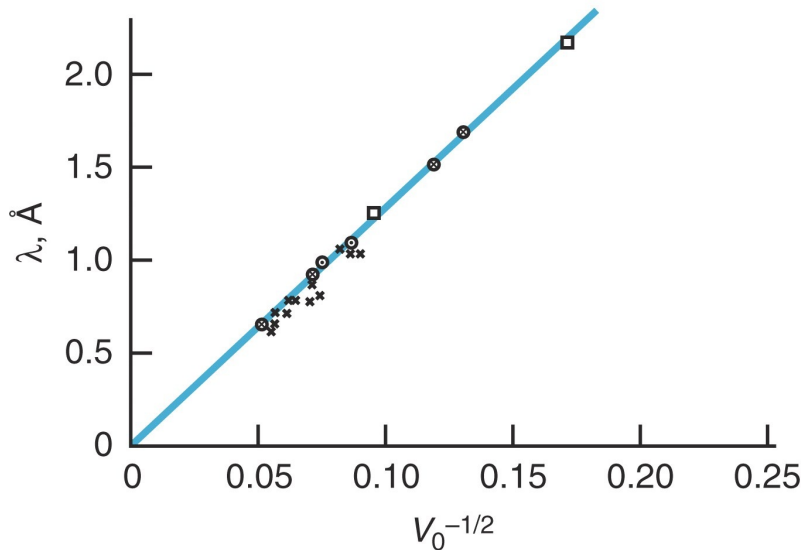
So, he could express energy in terms of momentum.

- If he defined the wavelength of a particle as

$$\lambda = \frac{h}{p}$$

he could get something which worked in both models.

# Davisson-Germer vs. Electron Energy



# How Strange is This?

## A Quote from Davisson:

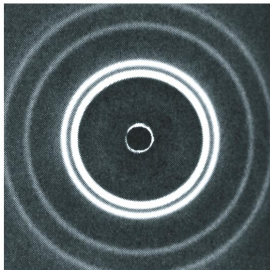
We think we understand the regular reflection of light and X-rays - and we should understand the reflection of electrons as well if only electrons were waves instead of particles...It is rather as if one were to see a rabbit climbing a tree and were to say "Well, that is a rather strange thing for a rabbit to be doing, but after all it is really nothing to get excited about. Cats climb trees - so that if the rabbit were only a cat, we would understand its behaviour perfectly."

## A Quote from Bohr:

Anyone who is not shocked by quantum theory has not understood a single word.

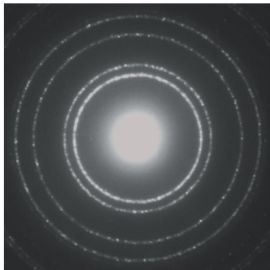
# Interference and Diffraction of Matter

(a) X-ray diffraction pattern



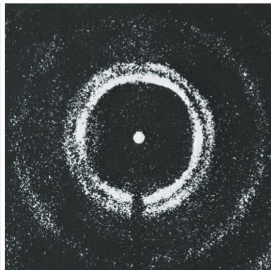
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(b) Electron diffraction pattern



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(c) Neutron diffraction pattern



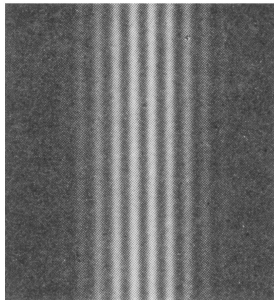
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- Numerous experiments verified that the diffraction and interference behaviours of light were replicated for matter.
- Electrons, neutrons and whole atoms have been shown to diffract just like X-rays!

# Matter in the Double Slit Experiment

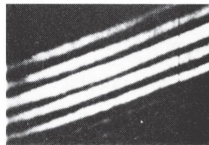
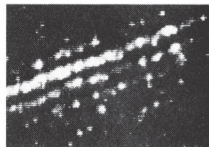
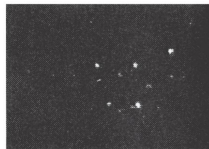
The double slit experiment is what originally convinced us that light was a wave. What does matter do?

(a) Double-slit interference of electrons



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Electrons double slit

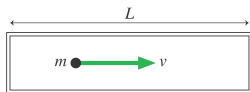


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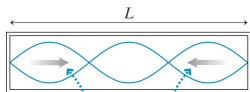
Electrons one at a time

# Energy is Quantized (25.5)

- (a) A classical particle of mass  $m$  bounces back and forth between the ends.



- (b) Matter waves moving in opposite directions create standing waves.



Matter waves travel  
in both directions.

- We know that waves confined between two boundaries for a standing wave. What does that imply for matter confined to a box?
- If the matter wave becomes a standing wave we know

$$\lambda_n = \frac{2L}{n}, n = 1, 2, 3, \dots$$

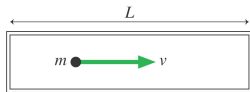
- We also know that the particle has wavelength  $\lambda = h/p$ .

$$p_n = n \left( \frac{h}{2L} \right), n = 1, 2, 3, \dots$$

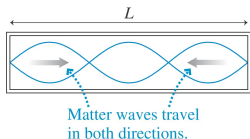
The momentum of the particle has only certain allowed values!!!

# Energy is Quantized (25.5)

- (a) A classical particle of mass  $m$  bounces back and forth between the ends.



- (b) Matter waves moving in opposite directions create standing waves.



- We know that energy and momentum are related by  $E = p^2/2m$  giving

$$E_n = \frac{1}{2m} \left( \frac{hn}{2L} \right)^2 = \frac{h^2}{8mL^2} n^2, n = 1, 2, 3, \dots$$

- Particles in a box can only have certain allowed energies! This is the **quantization of energy**.
- $n$  is a **quantum number** which characterizes the energy level of the particle in the box.
- Notice that this also says that the particle has a minimum energy. It must always be in motion!
- Matter is more complicated than it looks!

## A Quote from de Broglie:

On the one hand the quantum theory of light cannot be considered satisfactory since it defines the energy of a light corpuscle by the equation  $E = hf$  containing the frequency  $f$ . Now a purely corpuscular theory contains nothing that enables us to define a frequency; for this reason alone, therefore, we are compelled, in the case of light, to introduce the idea of a corpuscle and that of periodicity simultaneously. On the other hand, determination of the stable motion of electrons in the atom introduces integers, and up to this point the only phenomena involving integers in physics were those of interference and of normal modes of vibration. This fact suggested to me the idea that electrons too could not be considered simply as corpuscles, but that periodicity must be assigned to them also" - from Louis de Broglie's Nobel acceptance speech (1929)