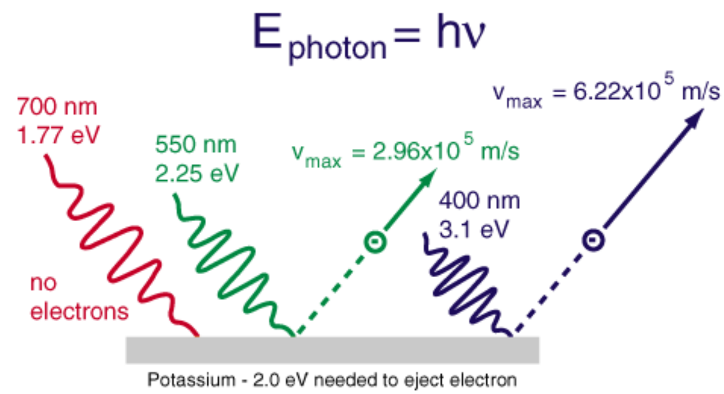
Announcements

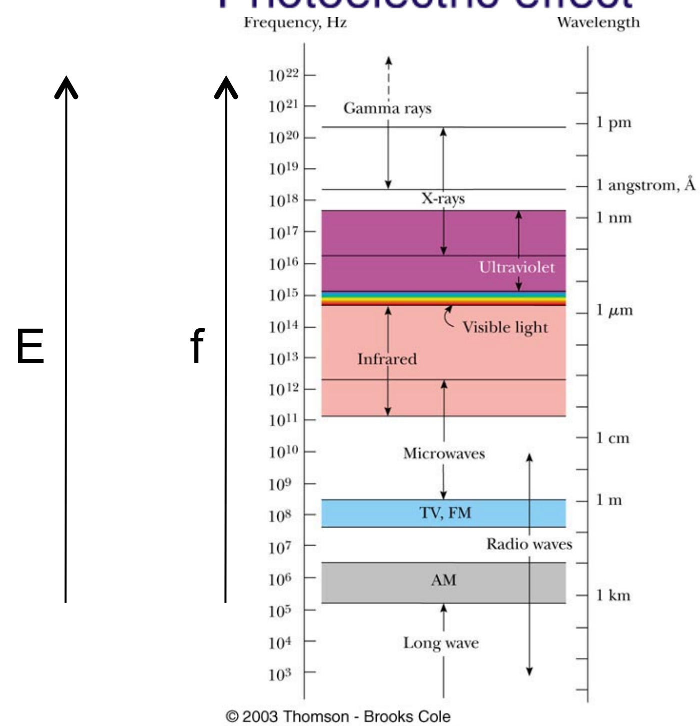
- Help room hours (1248 BPS)
  - Ian La Valley(TA)
  - Mon 4-6 PM
  - Tues 12-3 PM
  - Wed 6-9 PM
  - Fri 10 AM-noon
- Third hour exam Thursday Dec 6
- The textbook doesn't cover the material on relativity but in addition to my lecture notes, you can consult the web, for example

  http://www.phys.unsw.edu.au/einsteinlight/#top
- Final Exam Tuesday Dec 11 7:45-9:45 AM

Photoelectric effect

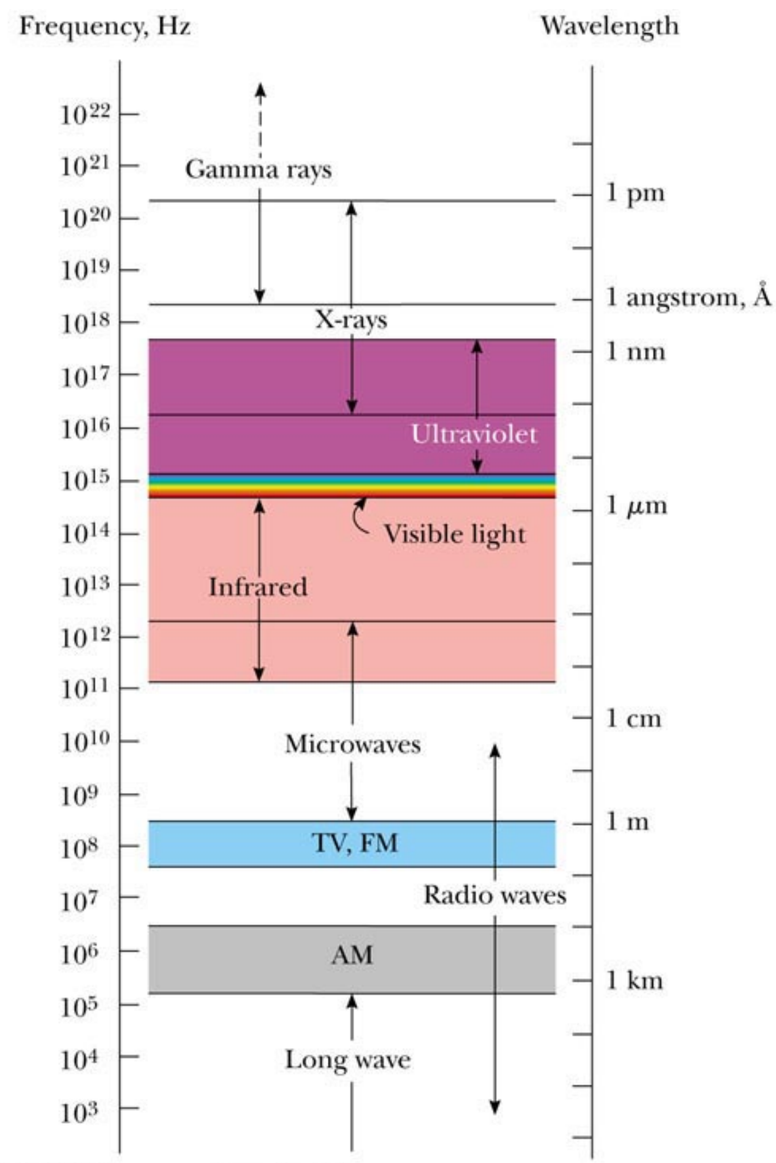
- This is one of the papers that Einstein wrote in 1905
  - and it is actually for this paper that he won the Nobel prize
- Explained a very puzzling experimental measurement
  - shine a very bright light on a surface
  - can you kick electrons out from the surface?
- Classical picture
  - a more intense light will eject more electrons
- Actual result
  - no electrons will be ejected unless the frequency of the light is high enough
    - red light does not work, green light does
- Einstein: EM radiation comes in packets called photons
  - each photon has an energy E=hf
  - where h is Planck's constant again
  - green photons have a greater energy than red photons (higher frequency)





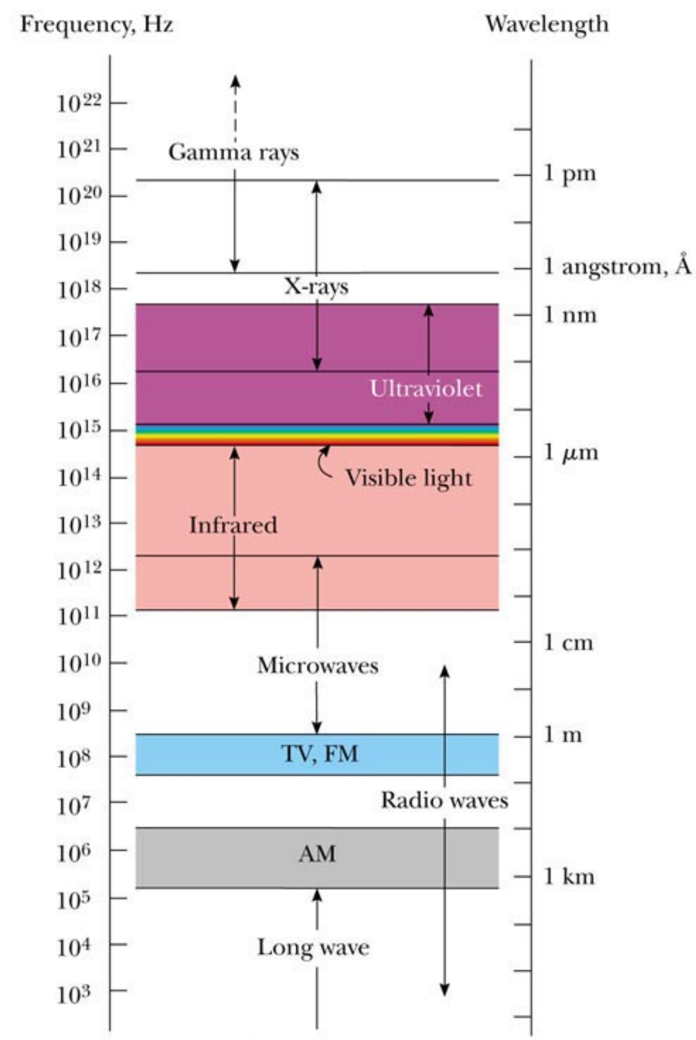
Can cellphones cause cancer?

- Electromagnetic radiation can cause cancer by ionizing (knocking electrons off of) atoms, creating mutations in DNA
- This is an example of the particle nature of EM radiation
- But the energy of the photons is equal to hf
- Ultraviolet radiation (and higher frequencies) can cause cancer (the danger of too much sun exposure)
- Microwave photons have 10,000 times less energy than UV photons, cannot ionize atoms, and cannot cause DNA mutations



Electromagnetic radiation

- We can say that the smaller the wavelength of the EM radiation, the more likely the behavior is to be particle-like
- The larger the wavelength, the more likely it is to be wavelike
- So X-rays often behave as particles; radio waves rarely do



Visible light in between

Wave-particle duality

- Light has a particle a nature as well as a wave nature
  - the higher the frequency, the more often light behaves as a particle
- Suppose I consider a photon of yellow light with a frequency of around 10^{15} hz
- How much energy is in one photon of yellow light?

E=hf
λ=c/f

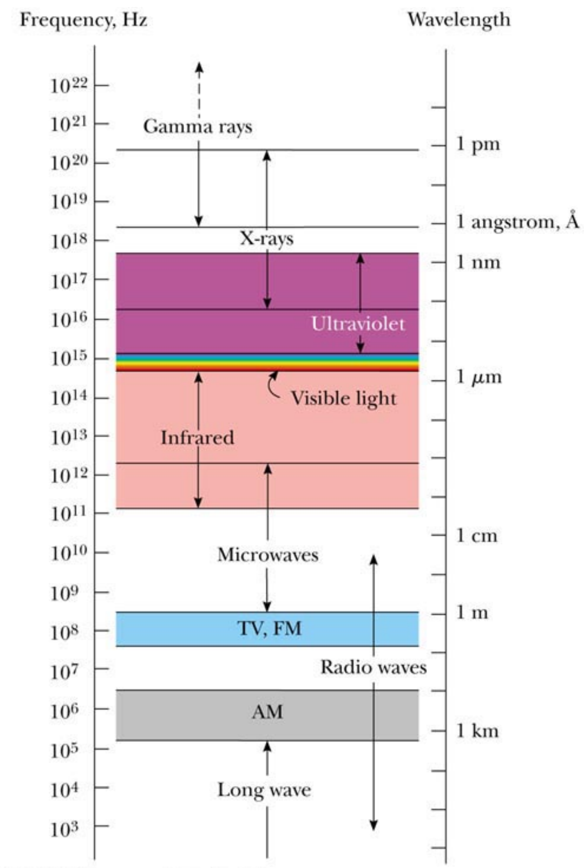
$$E = hf = (6.63X10^{-34}m^2kg/s)(1X10^{15}s^{-1})$$

$$E = 6.6X10^{-19}J$$

- We said that the intensity of sunlight is around 1000 W/m^2; suppose all of that were in the form of yellow photons: how many photons?

$$1000kW = 1000J/s$$

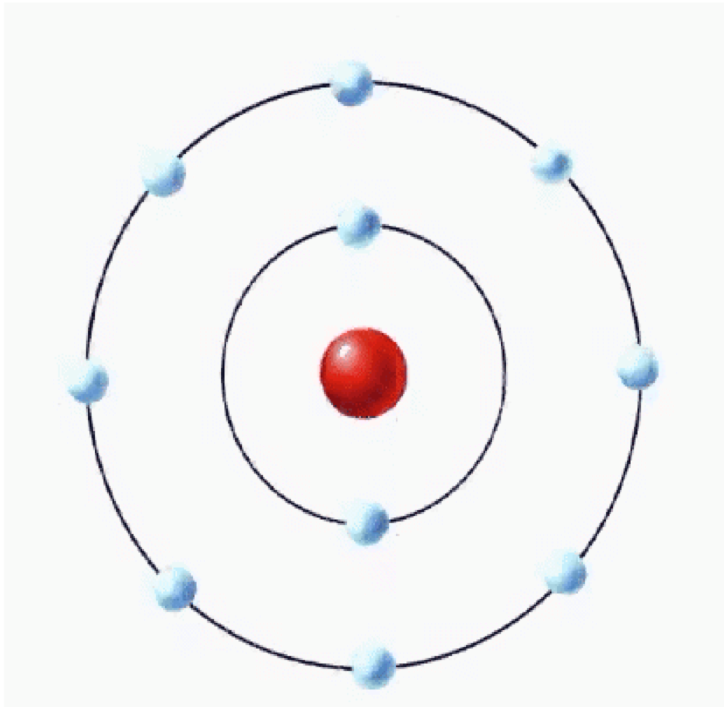
$$\frac{1000J}{6.6X10^{-19}J} = 1.5X10^{21}\,photons$$



So normal intensity of light consists of many photons. We usually don't see the particle nature.

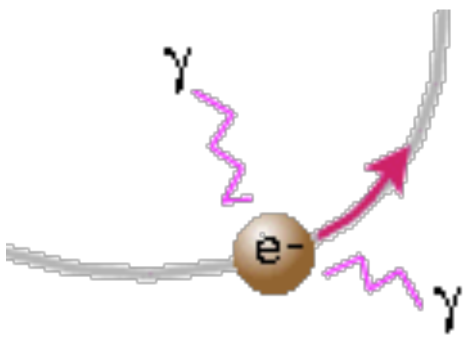
Bohr came up with the Solar System model

- Distant electrons orbit a massive nucleus due to the electromagnetic attractive force between the positive and negative charges
- The size of the nucleus here is greatly exaggerated
- If an atom were the size of Spartan Stadium, then the nucleus would be the size of a strawberry (at the 50 yard line)
- The vast majority of the atom is nothing but empty space
- That's why when you get rid of all of that empty space in a neutron star, you're left with an incredible density
  - since a neutron star is like a 10 km diameter nucleus



…there's always a but

- What held the positive charges in such a small nucleus
- And we learned that accelerated electric charges give off electromagnetic radiation
- If the electrons are orbiting around the nucleus, they're going in a circle and thus accelerating
- They should quickly spiral into the nucleus

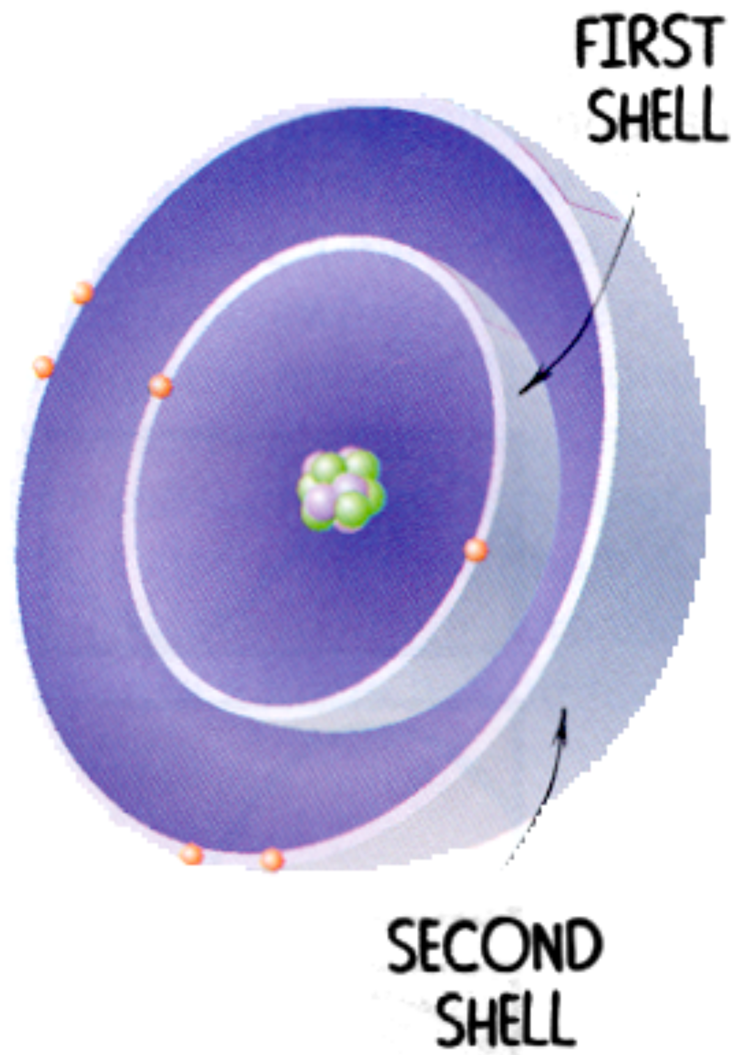


Niels Bohr came to the rescue

- Bohr applied the quantum principle originated by Planck and Einstein to the atom

Niels Bohr, Danish physicist (1885–1962)

- Only certain stable orbits exist for the electrons in an atom
- While in these orbitals, they cannot give off photons

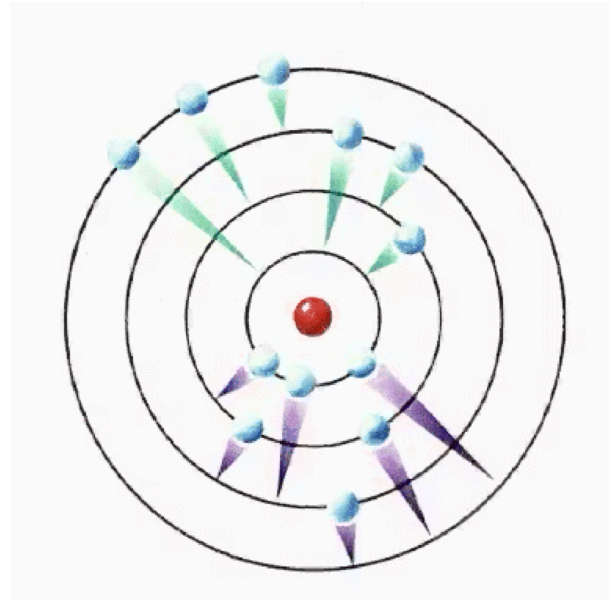


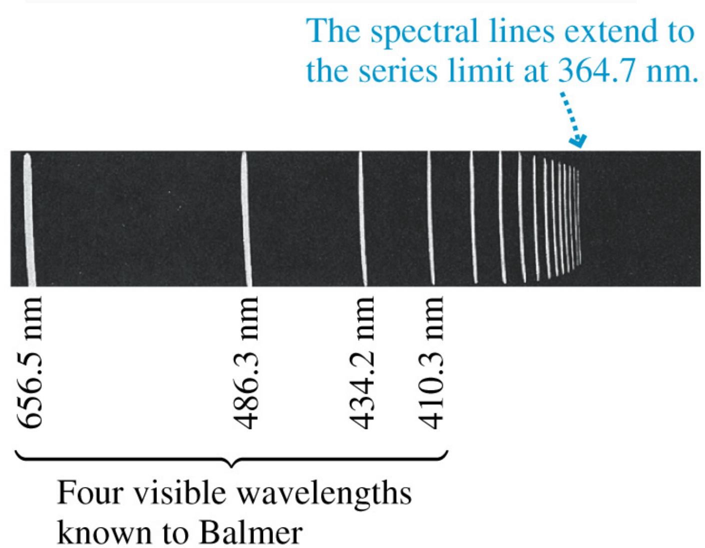
Quantum world

- Electrons can only move from one orbital to another by gaining or releasing photons (a quanta of energy, E=hf)

$$\lambda = \frac{91.18nm}{\left(\frac{1}{m^2} - \frac{1}{n^2}\right)}$$

- m=1 Lyman series (UV)
- m=2 Balmer series (visible)
- m=3 Paschen series (IR)

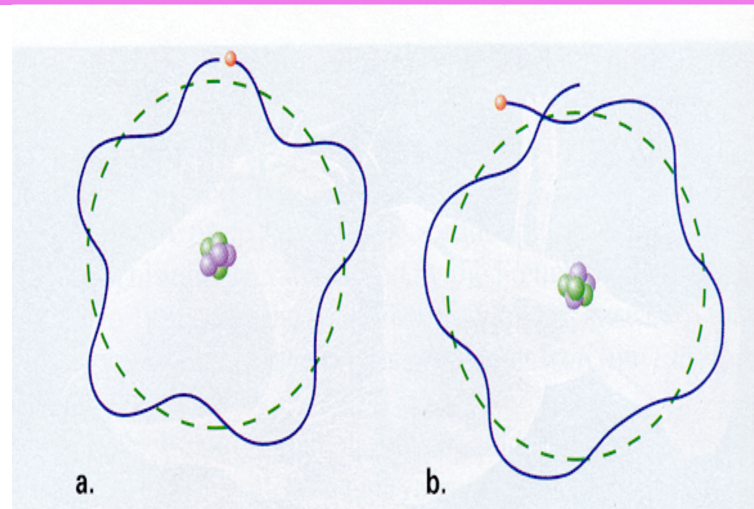




As promised, here is me sitting in Niels Bohr's chair

De Broglie

- Bohr's model worked, but it was very unsatisfactory
- Why did electrons have to stay in certain orbitals?
- Planets can have any radius in orbiting the Sun
- De Broglie suggested that all particles had a wave nature as well as a particle nature, with wavelength
  - $\lambda = h/p$ → anything involving quantum physics will involve h

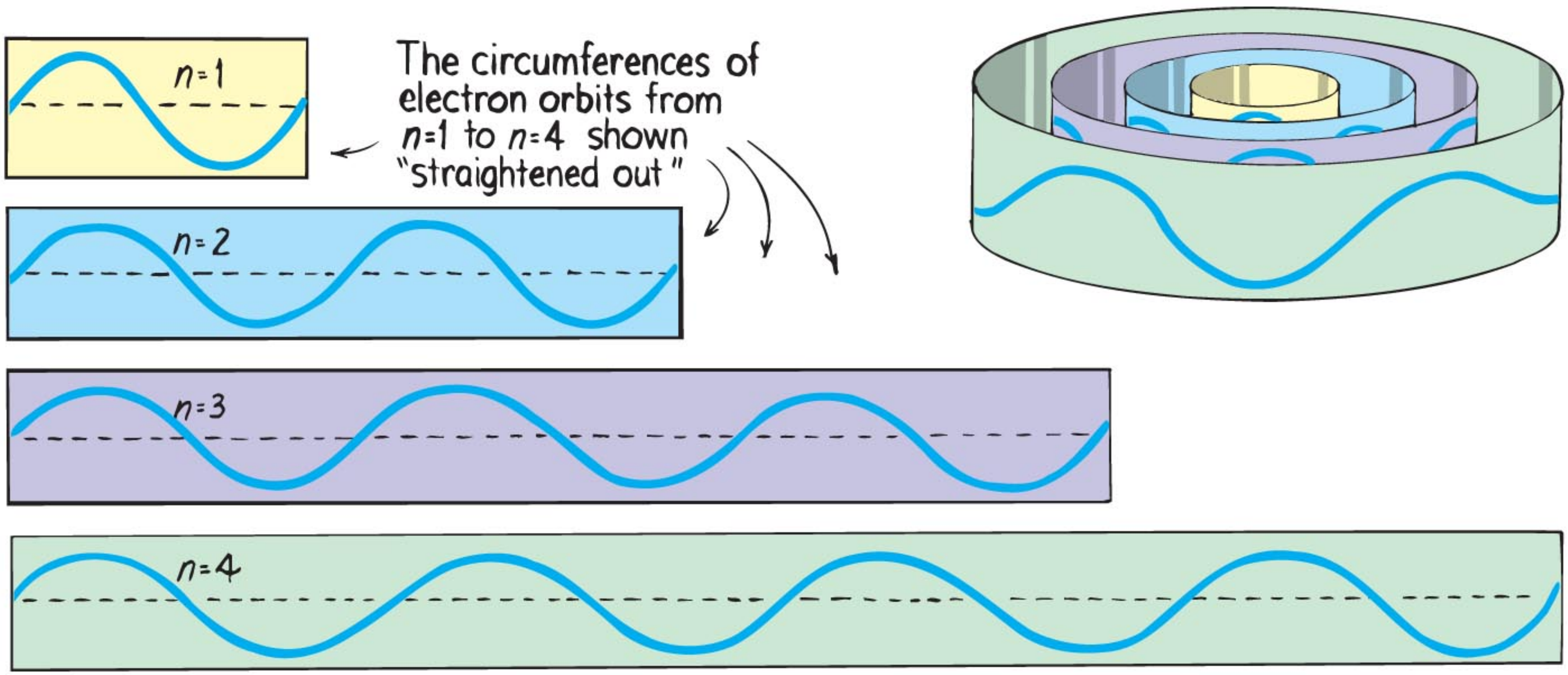


It was the wave nature of the electron that determined the nature of the orbits

You had to be able to fit an integral number of wavelengths in an orbital

Back to electron orbitals

This model explained why electrons don't spiral closer and closer to the nucleus. Each electron orbit is described by a standing wave. The circumference of the smallest orbit can be no smaller than one wavelength.



Quantum mechanics

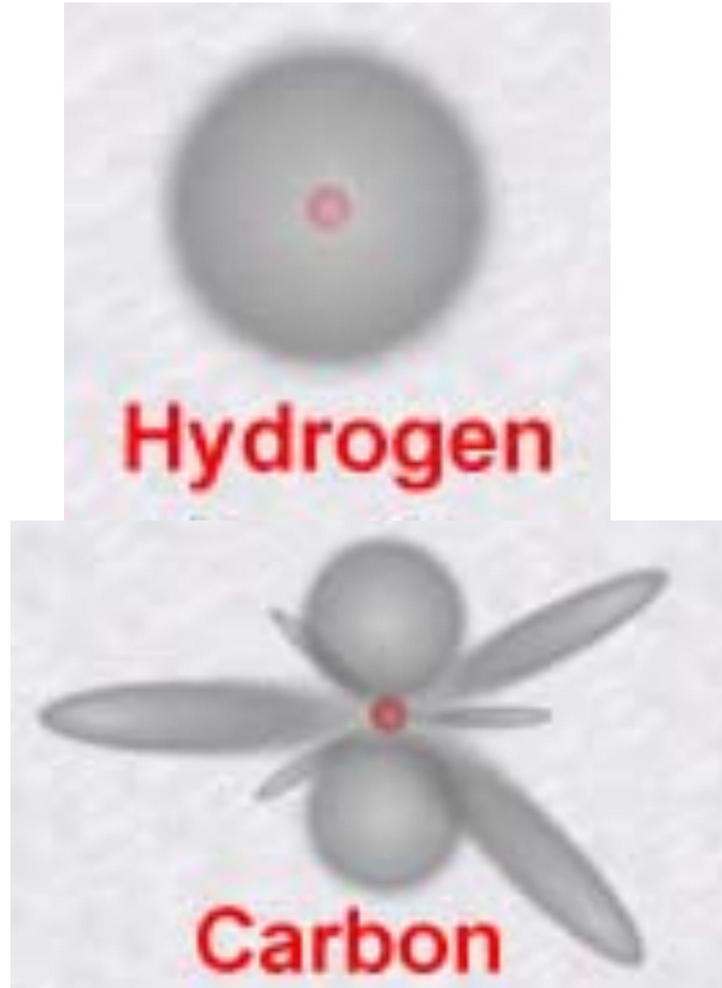
- In the 1920's physicists such as Wolfgang Pauli, Erwin Schroedinger, Werner Heisenberg and others realized that you cannot talk about a classical concept such as a fixed orbit for a subatomic particle like an electron
- Instead you can only describe the probability for an electron to be in a particular location at a particular time
- It was the end of certainty
- Everything in quantum mechanics is described in terms of probabilities
- We have to give up some of our cherished concepts from our macroscopic world when we deal with the sub-atomic world

Quantum mechanics

- It was the end of certainty
- Everything in quantum mechanics is described in terms of probabilities given in terms of the square of what is called the wave function $\psi(x)$
- The wave function is a solution to an equation called the Schroedinger equation

$$\left(-\frac{h2}{2m}\nabla^2 + U\right)\psi = ih\frac{\partial\psi}{\partial t}$$

- Schroedinger's equation plays the same role in quantum mechanics that Newton's equation (a=F/m) plays in classical physics
- The matter waves in Schroedinger's equation are mathematical entities not directly observable



$|\psi|^2$ gives the probability of finding The electron at a given location

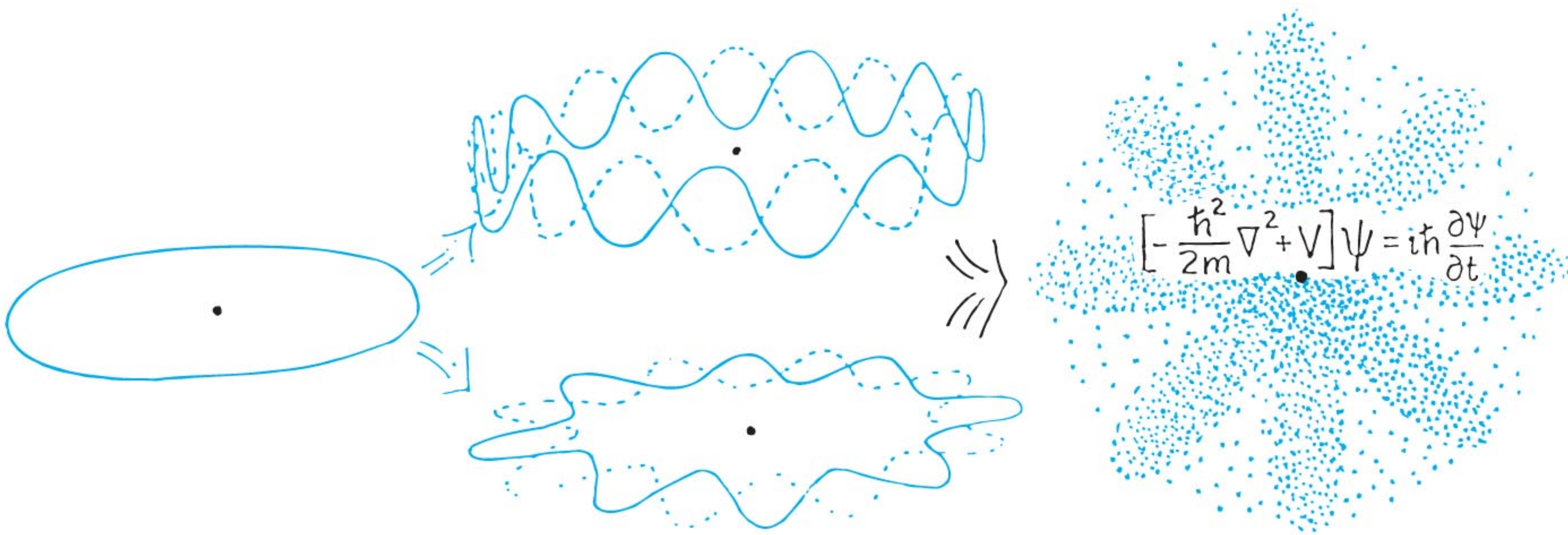
Quantum mechanics

- One can calculate the probability values for the momentum or energy or energy of a particle by solving the Schroedinger equation
- We can't talk about the specific location of an electron at a given moment in time, only the probability that it is at a particular location at a particular moment in time
- Its most probable location is at the average distance from the nucleus for the orbitals defined by Niels Bohr

$|\psi|^2$ gives the probability of finding The electron at a given location

Progression in understanding

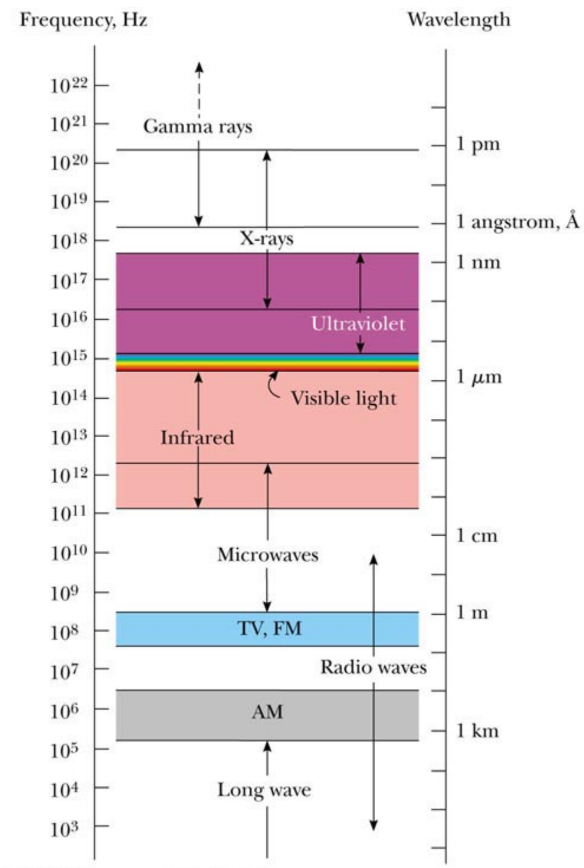
We went from the orbitals described by Niels Bohr to de Broglie's standing waves to a probability cloud describing the electron location in about 1 decade (1918-1928).



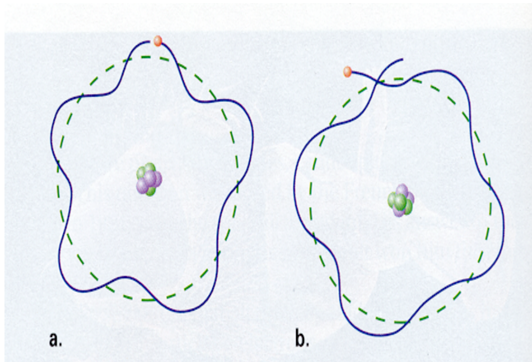
Wave-particle duality

- Light has a particle nature as well as a wave nature
  - the higher the frequency, the more often light behaves as a particle
- Particles have a wave nature as well as a particle nature
  - so particles passing through a narrow slit will diffract, just as a wave would

$E=hf$
$\lambda=c/f$
$\lambda=hc/E$
$\lambda=h/p$



$\lambda=h/p$



Heisenberg Uncertainty Principle

- Werner Heisenberg
- German physicist who in the 1920's was one of the founders of quantum mechanics
- Most of these revolutionaries were in their early 20's
- Quantum mechanics was known as "boy physics"
- Perhaps most famous for his uncertainty principle which related the precision with which you could measure complementary variables, like energy and time, or position and momentum
- We'll discuss him later as the leader of the Nazi atomic bomb project

The Heisenberg Uncertainty Principle

180 W. Heisenberg.

ermöglichen, als es der Gleichung (1) entspricht, so wäre die Quantenmechanik unmöglich. Diese Ungenauigkeit, die durch Gleichung (1) festgelegt ist, schafft also erst Raum für die Gültigkeit der Beziehungen, die in den quantenmechanischen Vertauschungsrelationen

$$pq - qp = \frac{h}{2\pi i}$$

ihren prägnanten Ausdruck finden; sie ermöglicht diese Gleichung, ohne daß der physikalische Sinn der Größen p und q geändert werden müßte.

Für diejenigen physikalischen Phänomene, deren quantentheoretische Formulierung noch unbekannt ist (z. B. die Elektrodynamik), bedeutet Gleichung (1) eine Forderung, die zum Auffinden der neuen Gesetze nützlich sein mag. Für die Quantenmechanik läßt sich Gleichung (1) durch eine geringfügige Verallgemeinerung aus der Dirac-Jordanschen Formulierung herleiten. Wenn wir für den bestimmten Wert η irgend eines Parameters den Ort q des Elektrons zu q' bestimmen mit einer Genauigkeit q_1, so können wir dieses Faktum durch eine Wahrscheinlichkeitsamplitude $S(\eta, q)$ zum Ausdruck bringen, die nur in einem Gebiet der ungefähren Größe q_1 um q' von Null merklich verschieden ist. Insbesondere kann man z. B. setzen

$$S(\eta, q) \text{ prop } e^{-\frac{(q-q')^2}{2q_1^2} - \frac{2\pi i}{h} p'(q-q')}, \quad \text{also } S\bar{S} \text{ prop } e^{-\frac{(q-q')^2}{q_1^2}}. \qquad (3)$$

Dann gilt für die zu p gehörige Wahrscheinlichkeitsamplitude

$$S(\eta, p) = \int S(\eta, q) S(q, p)\, dq. \qquad (4)$$

Für $S(q, p)$ kann nach Jordan gesetzt werden

$$S(q, p) = e^{\frac{2\pi i p q}{h}}. \qquad (5)$$

Dann wird nach (4) $S(\eta, p)$ nur für Werte von p, für welche $\frac{2\pi(p-p')q_1}{h}$ nicht wesentlich größer als 1 ist, merklich von Null verschieden sein. Insbesondere gilt im Falle (3):

$$S(\eta, p) \text{ prop } \int e^{\frac{2\pi i(p-p')q}{h} - \frac{(q'-q)^2}{2q_1^2}}\, dq,$$

d. h.

$$S(\eta, p) \text{ prop } e^{-\frac{(p-p')^2}{2p_1^2} + \frac{2\pi i}{h} q'(p-p')}, \quad \text{also } S\bar{S} \text{ prop } e^{-\frac{(p-p')^2}{p_1^2}},$$

wo

$$p_1 q_1 = \frac{h}{2\pi}. \qquad (6)$$

- …or
  - "The more precisely the position is determined, the less precisely the momentum is known in this instant, and vice versa."
    --Heisenberg, uncertainty paper, 1927
- Mathematically, if I measure the position of a particle with a precision Δx and have a simultaneous measurement of the momentum with precision Δp_x, then the product of the two can never be less than $h/4\pi$ (Planck's constant again)
  - $\Delta x \Delta p_x > h/(4\pi)$
  - also, $\Delta E \Delta t > h/(4\pi)$

Example

- Suppose I have an electron whose velocity in the x direction I know to an accuracy of 0.545 m/s
- How well can I possibly know its momentum in the x direction?
- I know from the Heisenberg Uncertainty Principle that: $\Delta x \Delta p > h/(4\pi)$
  - $\Delta p = m_{electron} * \Delta v$
  - $\Delta x > h/(4\pi \Delta p)$

What does it mean?

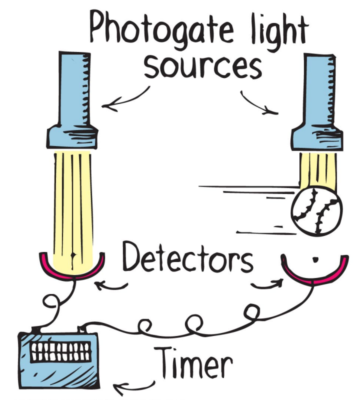
- A careless summary would be that "all things are uncertain", but this is not really correct
- "In the sharp formulation of the law of causality-- if we know the present exactly, we can calculate the future-it is not the conclusion that is wrong but the premise."
  --Heisenberg, in uncertainty principle paper, 1927

- Einstein could not acept this inherent uncertainty to the universe for the rest of his life
- Famous debate in the 5th Solvay Conference with Niels Bohr

Uncertainty principle

- The act of measuring something affects the quantity being measured
- For example, if we place a cool glass thermometer in a cup of coffee to measure its temperature, the temperature of the coffee is altered by the heat given to the thermometer

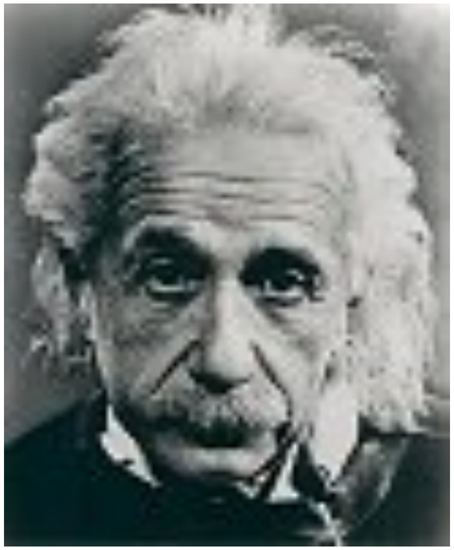
- Consider measuring the speed of a baseball by timing its passage between two photogates



- The baseball stops photons of light from reaching the detectors
- Practically speaking, the photons do not affect the motion of the baseball (much)
- But if this was an electron, the photons would change the motion of the electron

Einstein was disturbed

- His famous quote was
  - "God does not play dice with the universe"
- He felt that there were hidden variables, hidden dynamics, that, if we could see them, would return a deterministic understanding of our universe
- But the spooky nature of quantum mechanics has been confirmed over and over again



The Quantum Cafe

- http://www.pbs.org/wgbh/nova/elegant/program.html
- Chaper 5 of first hour

Review:Complementarity

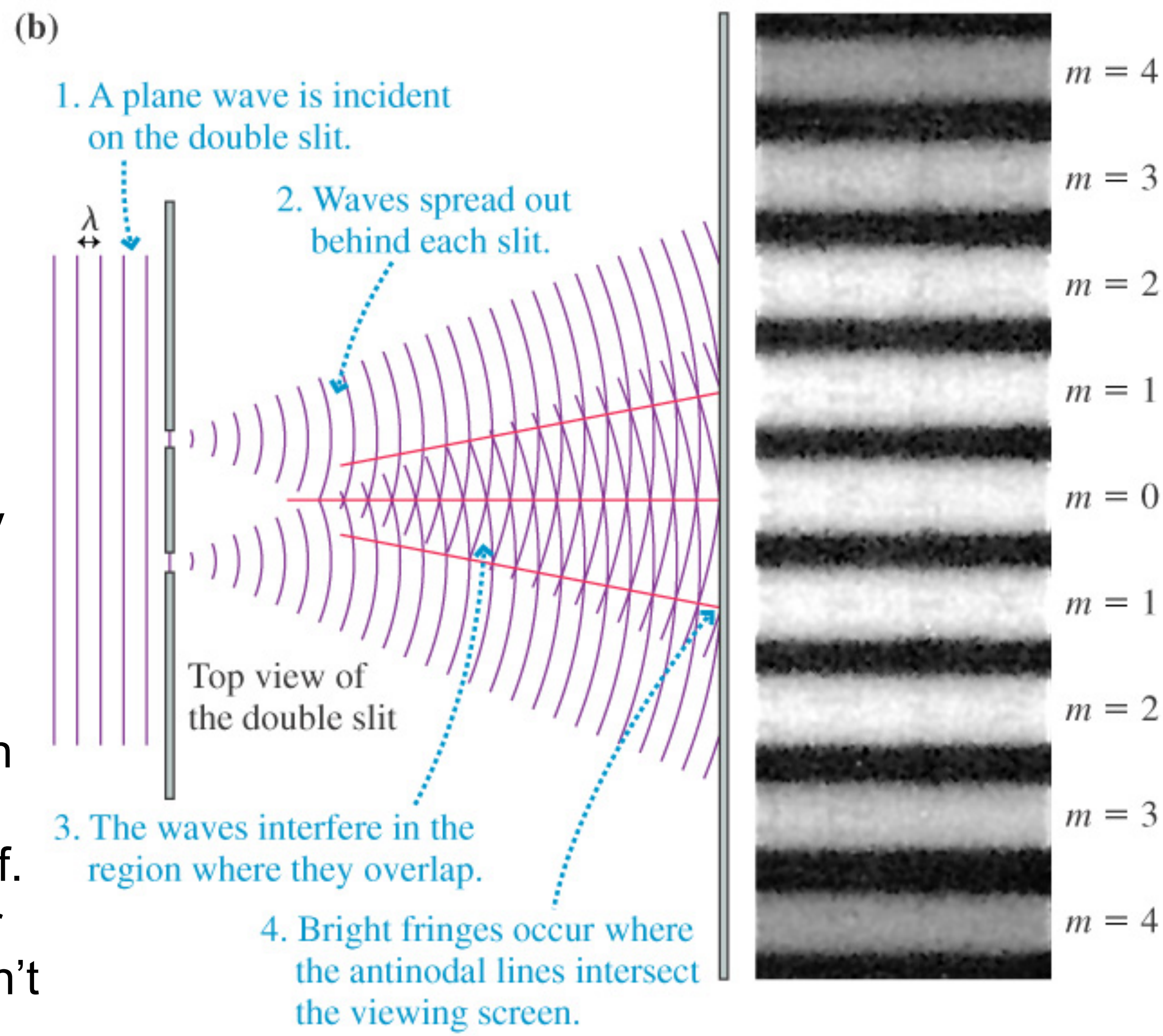
- The realm of quantum physics can seem confusing
- Light waves that diffract and interfere deliver their energy in packages called photons (particles)
- Electrons that move through space in straight lines and experience collisions as if they were particles distribute themselves in interference patterns as if they were waves
- Light and electrons exhibit both wave and particle characteristics
- Niels Bohr called this property complementarity
  - light and electrons (or any subatomic particle) appear as either particles or waves depending on the type of experiment conducted
  - experiments designed to examine individual exchanges of energy and momentum bring out particle properties, while experiments designed to examine spatial distribution of energy bring out wavelike properties
- It's our problem that we want to think of something as either a particle or a wave

Remember inteference

A series of bright and dark fringes appears on the screen. Bright for constructive interference and dark for destructive interference.

The same pattern appears even if you cut down the light intensity so that only one photon goes through at a time.

But the photon has to go through either the top slit or the bottom slit, but it still interferes with itself. somehow it knows that the other slit is there, even though it doesn't so through it.
I told you quantum mechanics was spooky.



Clicker question

- In Heisenberg's uncertainty principle, momentum is linked with position and energy is linked with
  - a) also position
  - b) momentum
  - c) velocity
  - d) time
  - d) space

Clicker question

- In Heisenberg's uncertainty principle, momentum is linked with position and energy is linked with
  - a) also position
  - b) momentum
  - c) velocity
  - **d) time**
  - d) space

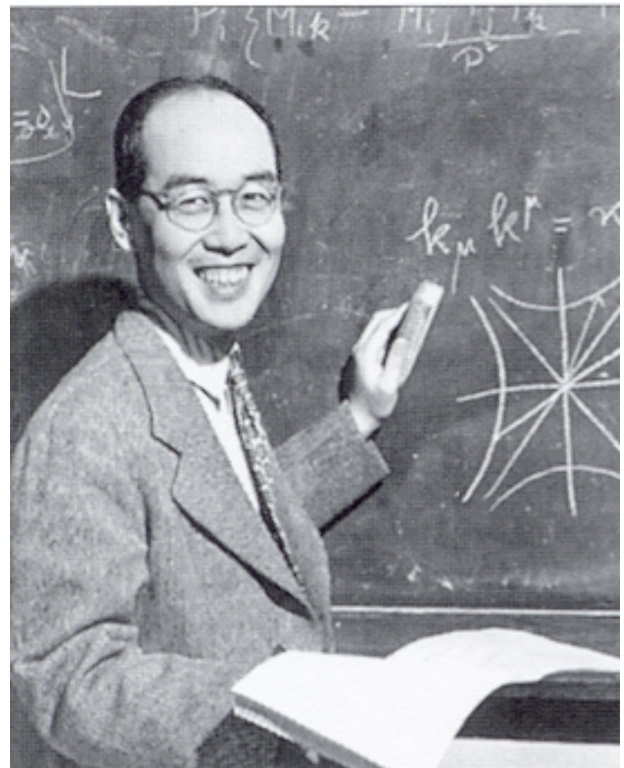
Fundamental Forces Interlude

- By mid 1930s, physicists thought they were close to figuring out the fundamental forces acting between particles.
- With the photon, a picture had arisen of the ElectroMagnetic Force as

"*charged particles interacting through the exchange of photons.*"

- Hideki Yukawa suggested a similar model to explain the strong nuclear force that was holding the protons and neutrons together inside the nucleus.
- So, in his model, a new particle whose exchange between nucleons produces the strong force.
- Theoretically, the new particle would have a mass between that of an electron and a nucleon, (~200 m_e) thus it got the name

Meson, Greek for “middle.”



Hideki Yukawa, Japanese physicist (1907 – 1981)