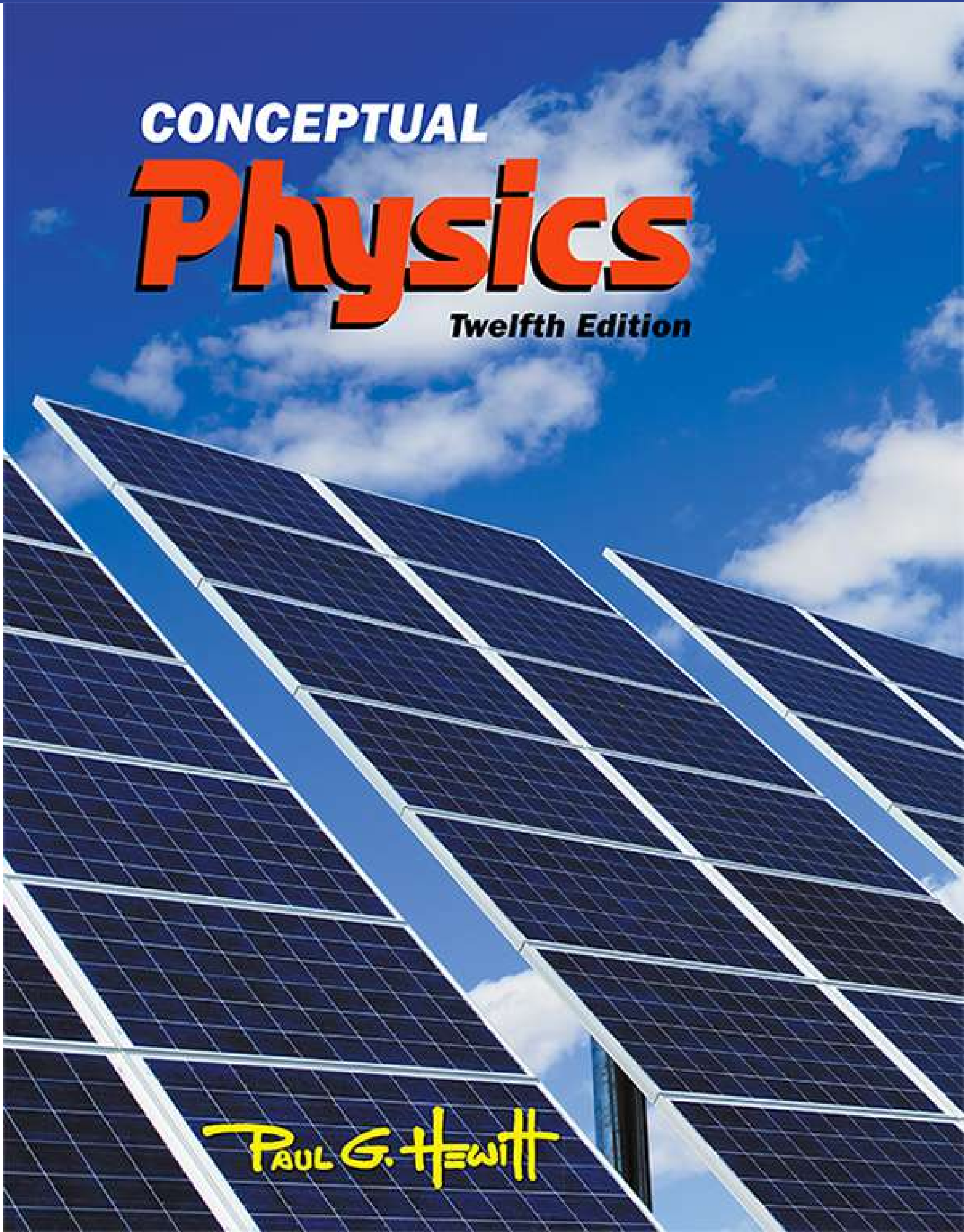
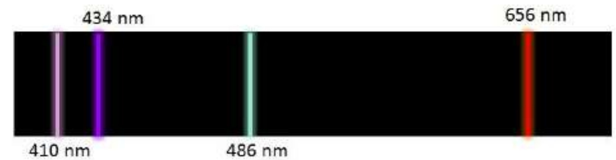
Lecture Outline

Chapter 32: The Atom and the Quantum

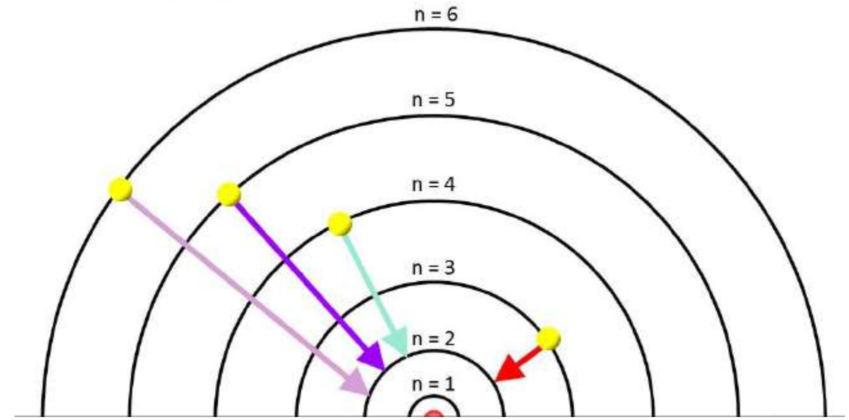


Review:

To explain this:

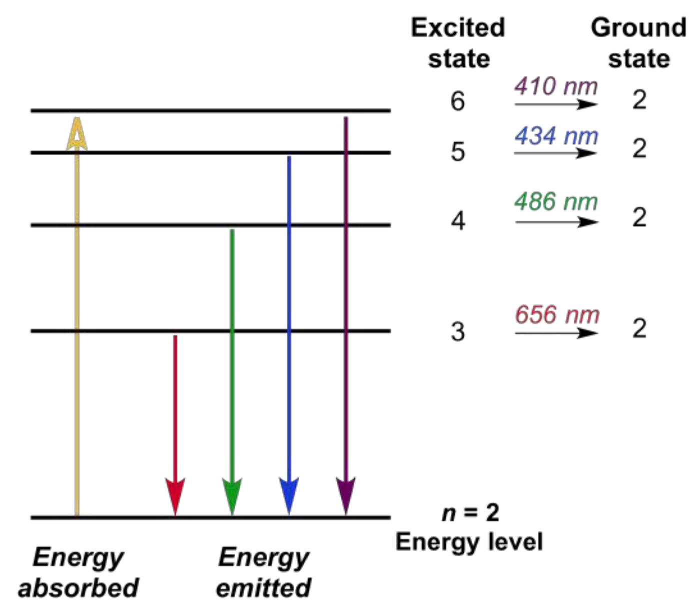


Bohr said that the electron could only be found at certain, special "orbitals" called stationary states:



And each stationary state had a special energy:

A photon is created when the electron jumps a level:



Why the distinct levels?

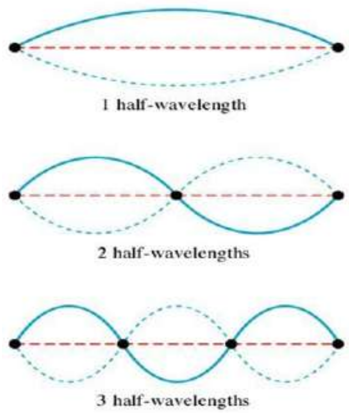
Remember electron waves?

- Louis de Broglie hypothesized that a wave is associated with every particle.
  - The wavelength λ of a "matter wave" is inversely related to a particle's momentum:

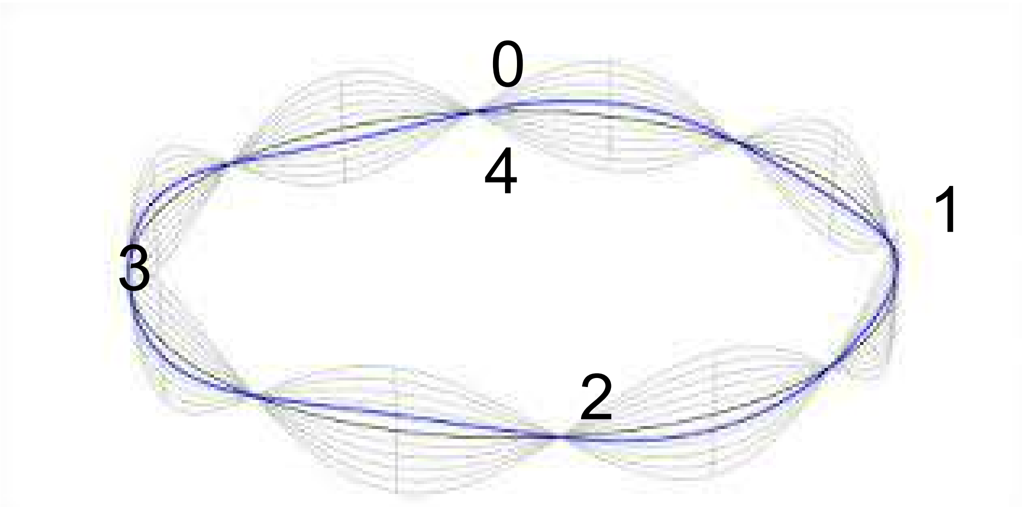
$$\lambda = \frac{h}{momentum} = \frac{h}{mass\ x\ speed}$$

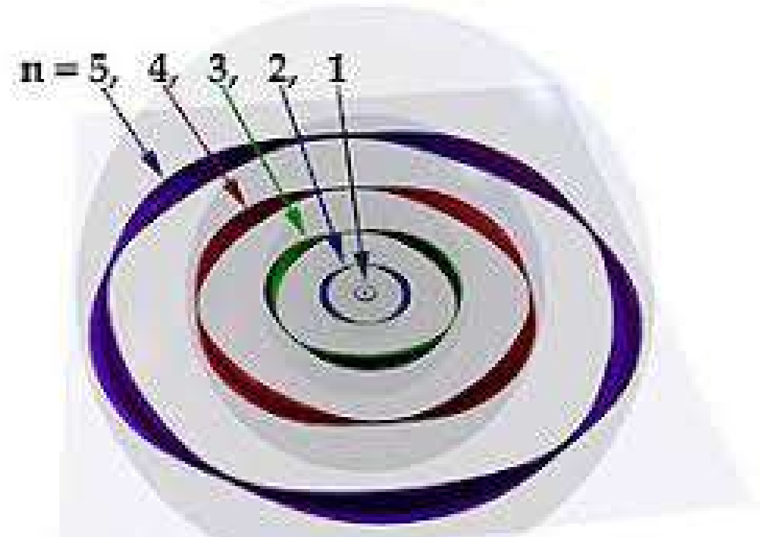
- de Broglie showed that a Bohr orbit exists where an electron wave closes on itself *constructively*.

The electron wave becomes a standing wave, like a wave on a musical string.



- In this view, the electron is thought of not as a particle located at some point in the atom, but as if its mass and charge were spread out into a standing wave surrounding the atomic nucleus with an **integral number of wavelengths** fitting evenly into the circumferences of the orbits.



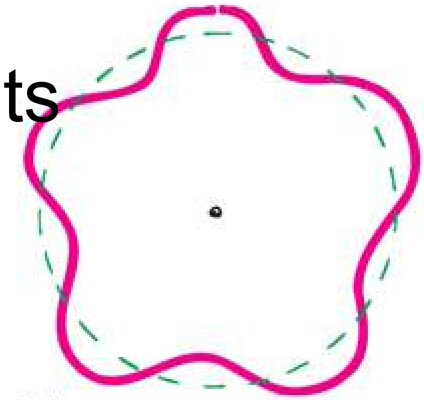


Niels Bohr - Louis de Broglie atom, 1924

a) An orbiting electron forms a standing wave only when the circumference of its orbit is equal to a whole-number multiple of the wavelength.

→ *Constructive Interference*

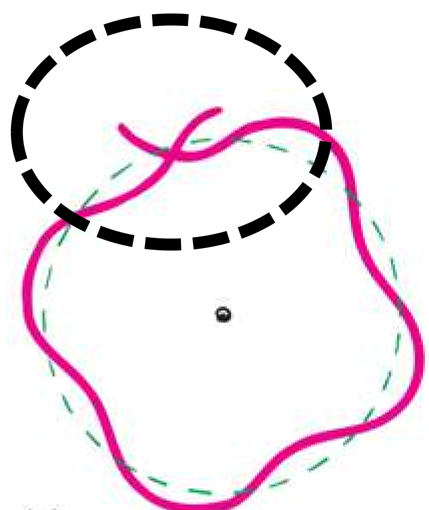
→ orbit allowed



(a)

b) When the wave does not close in on itself in phase, it undergoes *destructive interference.*

Hence, orbits exist only where waves close in on themselves in phase.



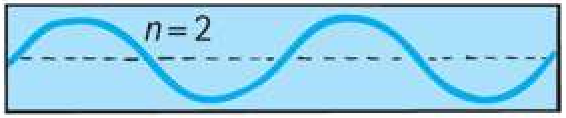
(b)

- The circumference C of the innermost (ground state, n = 1) orbit, according to this picture, is equal to one wavelength.

C = 1λ

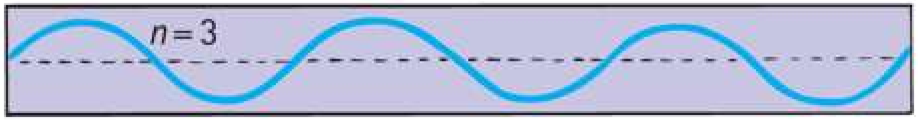
The second orbit (n = 2) has a circumference of two electron wavelengths.

C = 2λ



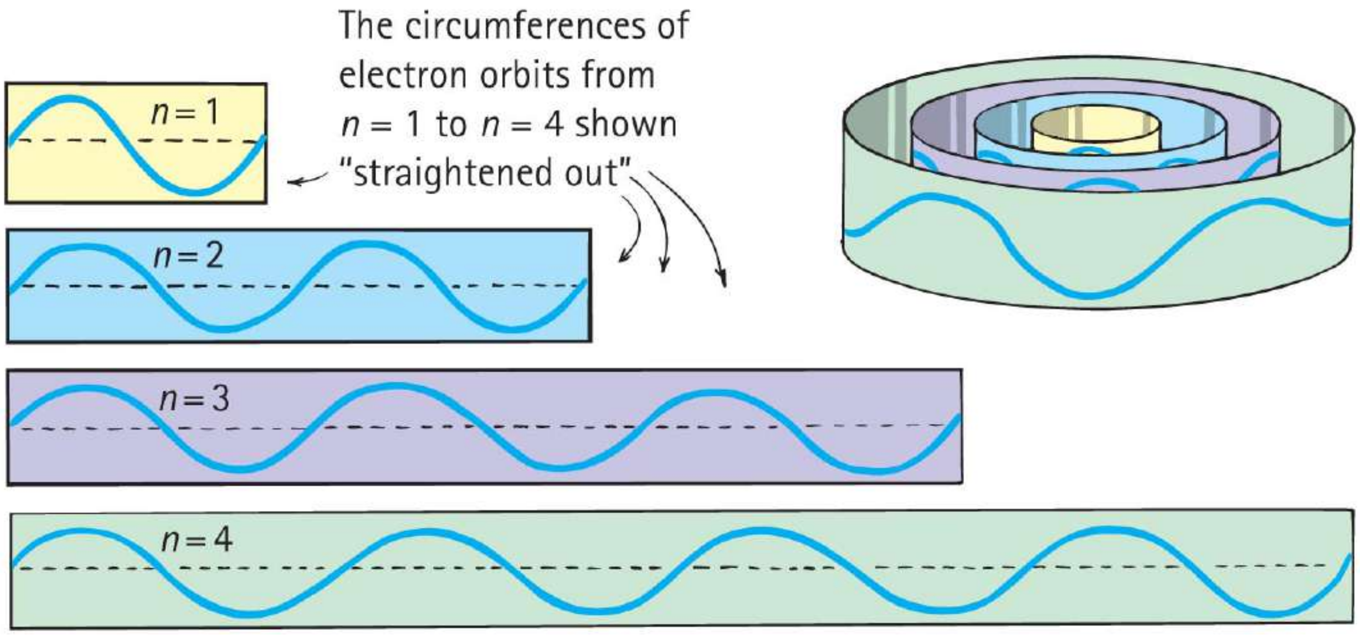
The third orbit (n = 3) has a circumference of three electron wavelengths

C = 3λ



etc.

- The electron orbits in an atom have discrete radii because the circumferences of the orbits are whole-number multiples of the electron wavelength.



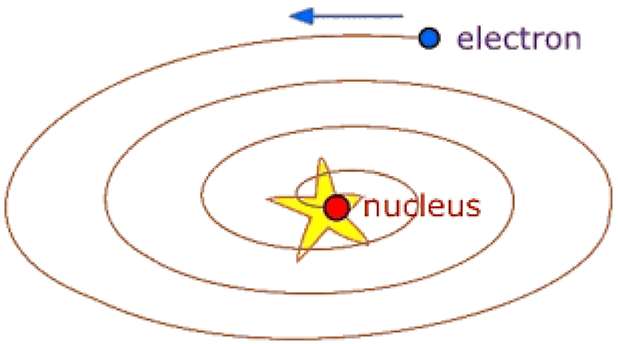
- This results in a discrete energy for each orbit.

Classwork:

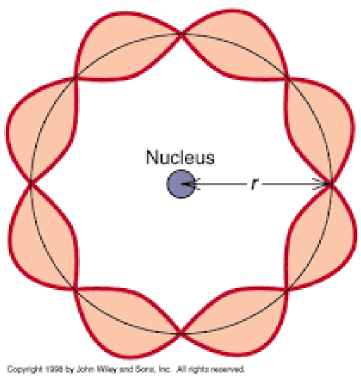
13. How does treating the electron as a wave rather than as a particle solve the riddle of why electron orbits are discrete?

14. According to the simple de Broglie model, how many wavelengths are there in an electron wave in the first orbit? In the second orbit? In the *n*th orbit?

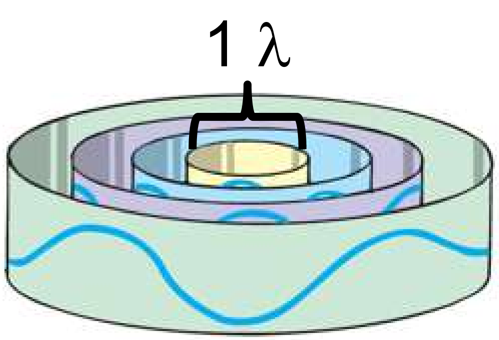
- This model explains why electrons don't spiral closer and closer to the nucleus, causing atoms to shrink to the size of the tiny nucleus.



- No fraction of a wavelength is possible in a circular (or elliptical) standing wave.



- If each electron orbit is described by a standing wave, the circumference of the smallest orbit can be no smaller than one wavelength.



Classwork

15. How can we explain why electrons don't spiral into the attracting nucleus?

Quantum Mechanics

- *Classical mechanics* is the study of how the macroscopic (large size) world works.
- Its fundamental equations are Newton's laws and Maxwell's equations for electromagnetism.

- *Quantum mechanics* is the study of the how the quantum (microscopic) world works.
- The fundamental equation of quantum mechanics is Schrödinger's wave equation, which is:

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

Schrödinger's wave equation:

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

It is the most fundamental equation in physics.

The solution to this equation is Ψ, a mathematical entity called a *wave function* (the Greek letter *psi*).

All the information about the matter waves is contained in the wave function.

Ψ describes how the matter wave moves in time.

Just one small problem—Schrödinger's equation and Ψ contain imaginary numbers ($i = \sqrt{-1}$)!!!!

Classwork

16. What does the wave function ψ represent?

Big problem:

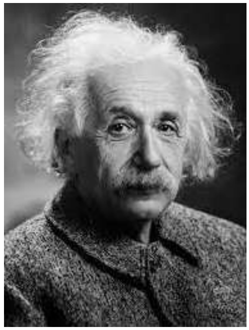
Ψ is an *imaginary* number. (It contains: $i = \sqrt{-1}$)

But Ψ^2 (usually written $|\Psi|^2$) **is a *real* number.**

So what does Ψ^2 represent?

Ψ^2 = the probability that the wave-particle will be found somewhere at some time.

The most accurate theory in physics allows you to only predict the probability of where a wave particle might be!



Einstein hated this idea of finding probabilities.

He said, "God does not play dice!"

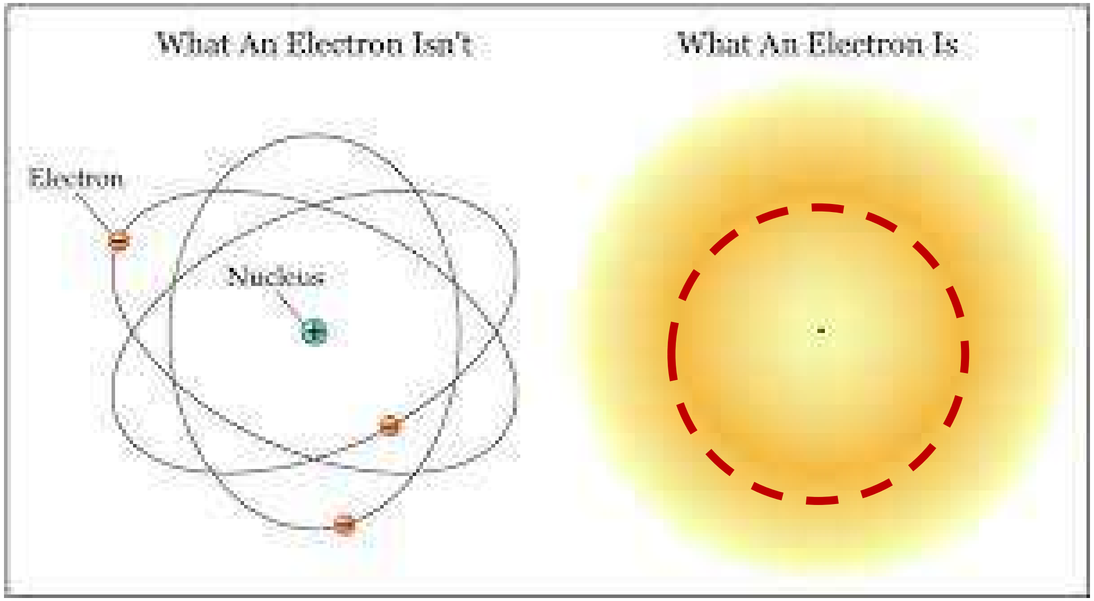
Classwork

17. How does the probability density function differ from the wave function?

Here is how it works:

That chance of finding an electron somewhere is from **0** (no chance) **to 1** (100% certain).

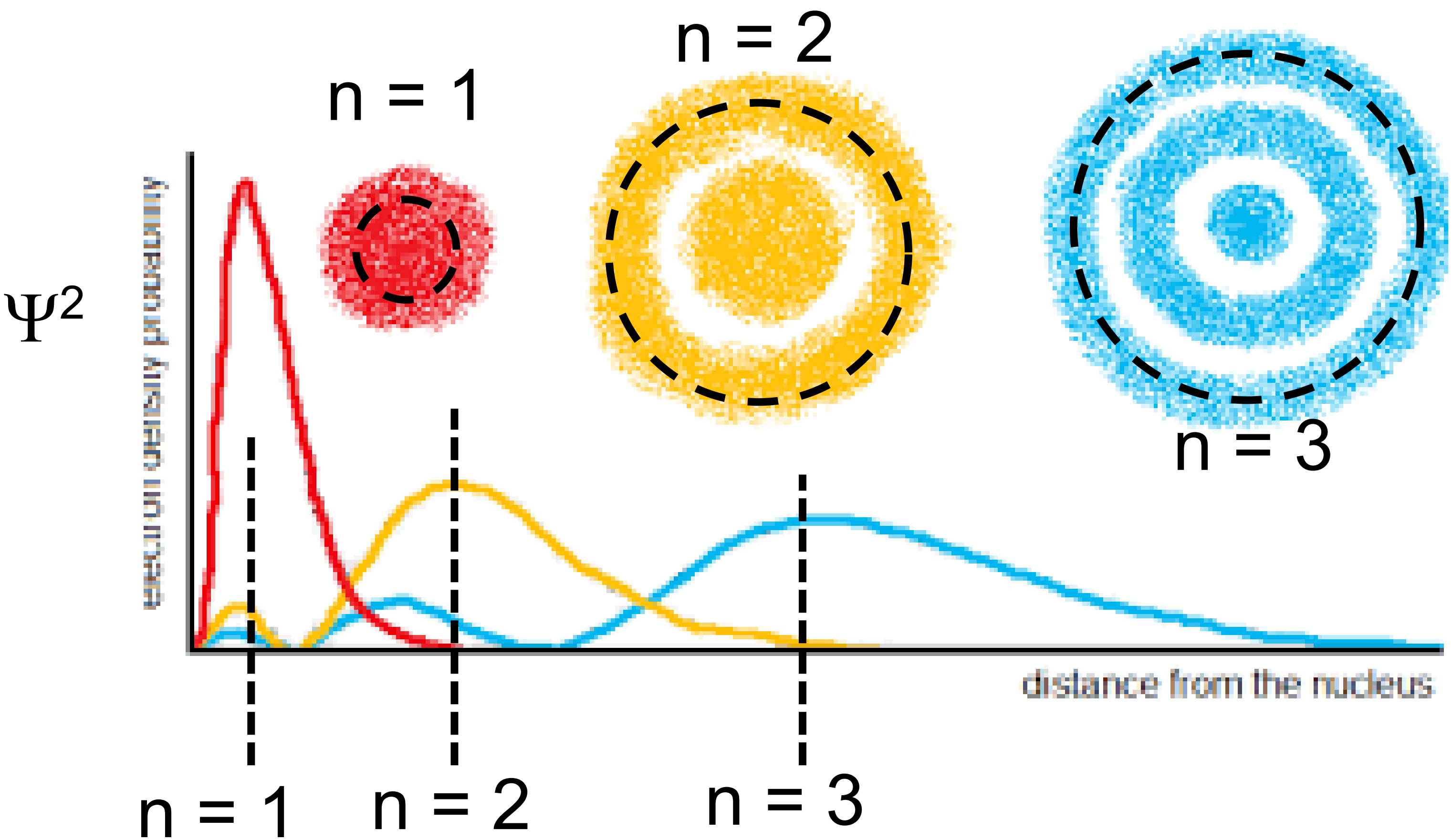
Ex: If $\Psi^2 = 0.40$ → The chance of finding electron = 40%



The probability density Ψ^2 is densest where the electron is most likely to be found: at the Bohr orbits!

There is even a small possibility of finding the electron inside of the nucleus!

Electron cloud ≈ Bohr orbits for H



Each cloud is densest at radius of a Bohr orbit.

Classwork

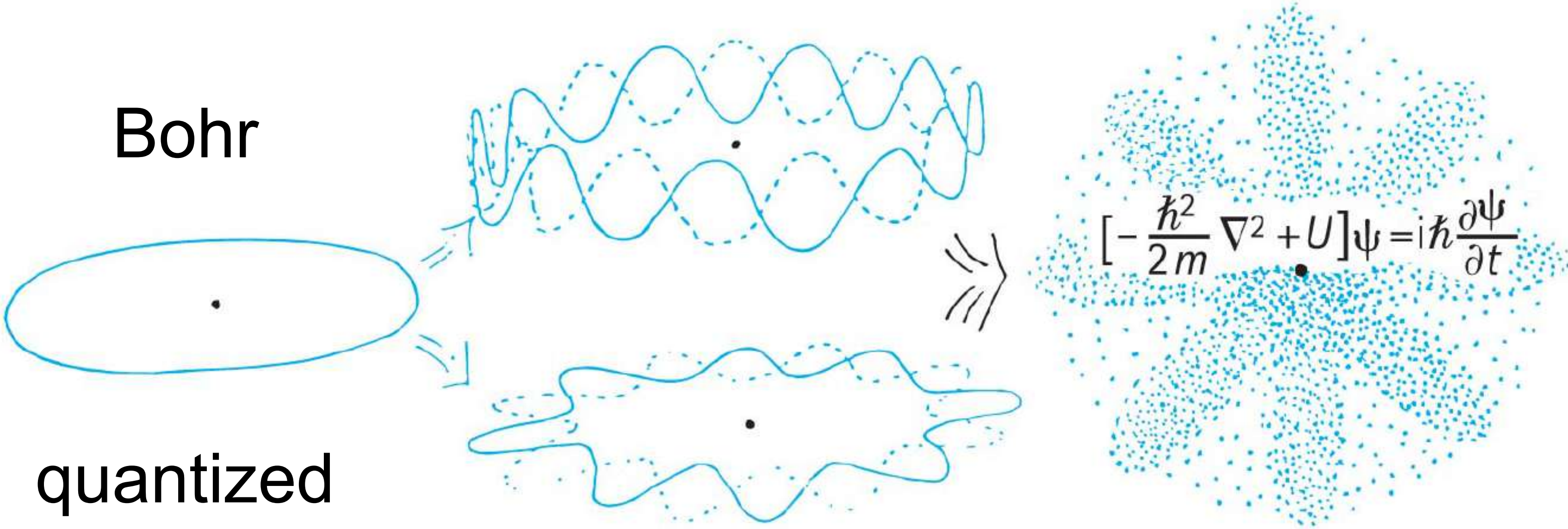
18. How does the probability cloud of the electron in a hydrogen atom relate to the orbit described by Niels Bohr?

- Historical progression of electron models:
- From simple to more sophisticated and accurate

Bohr

de Broglie

Schrodinger



quantized
orbits

electron
standing waves

probability
density cloud

Quantum Mechanics
CHECK YOUR NEIGHBOR

As to why electrons orbit in only certain orbits, a compelling explanation views orbital electrons as

A. particles that morph into waves.
B. standing waves.
C. planetary particles.
D. quantum particles.

Quantum Mechanics
CHECK YOUR ANSWER

As to why electrons orbit in only certain orbits, a compelling explanation views orbital electrons as

B. **standing waves.**

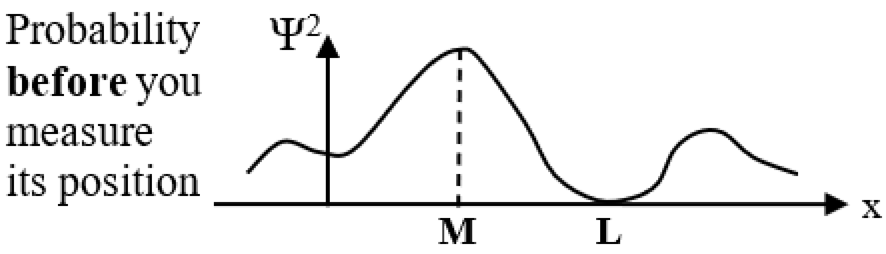
Explanation:

Standing waves are stable and close in on themselves in phase.

Quantum Mechanics in 5 word:
Don't look: wave.   Look: particle.

Ψ^2 is the probability of finding a particle somewhere:

Before measuring:

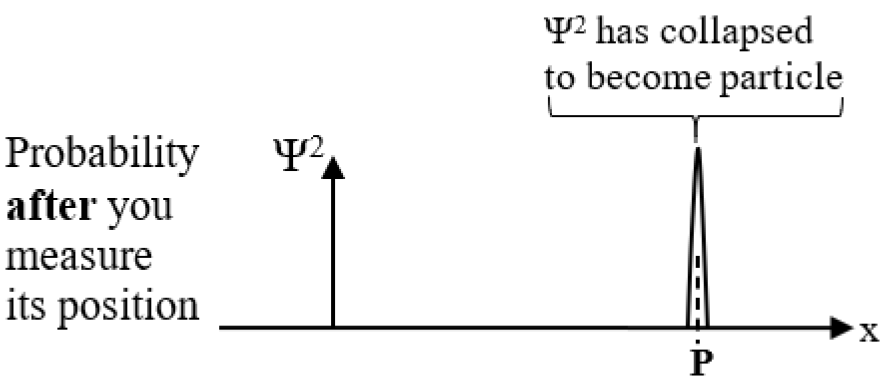


The wave function Ψ (or Ψ^2) isn't really anywhere.

M = most likely to find it

L = least likely to find it

After measuring:



The wave function Ψ collapses to a point P.

It is there—100% sure.

Observing it makes it appear as a particle!

Schrodinger's cat: *Background*

Sometimes there is more than one solution to Schrodinger's equation:

Let's say there are two solutions: Ψ_1 and Ψ_2.

Then, a "superposition" of Ψ_1 and Ψ_2 is also a solution:

new solution: $\Psi = a \cdot \Psi_1 + b \cdot \Psi_2$

where a and b are just numbers.

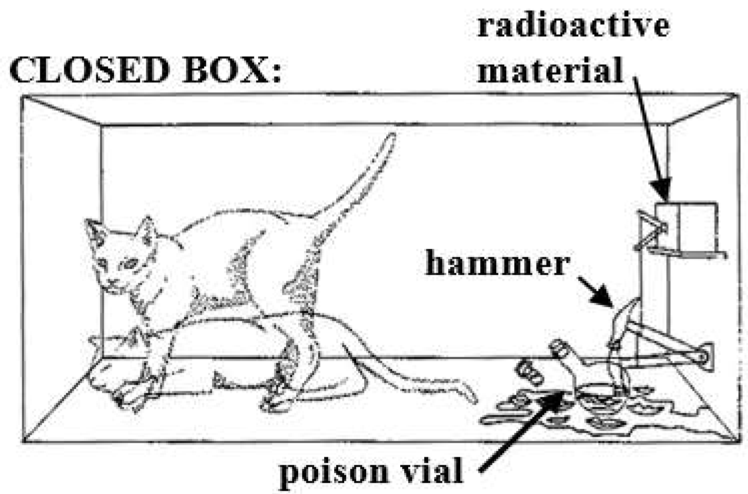
However, if you make a measurement or observation of Ψ, this sum must collapse to either Ψ_1 or Ψ_2.

Measure $\Psi \rightarrow$ you get either: Ψ_1

or: Ψ_2

Observing collapses the wave function Ψ.

A cat is placed in a box with radioactive material. If the material decays, it releases a hammer that breaks a vial containing a point that kills the cat. The radioactive material has a certain probability (chance) of decaying. The cat may be dead, it may be alive—you don't know until you observe by opening the box.



Schrodinger's equation has 2 solutions to this problem:

$$\Psi_1 = |alive> \quad \text{and} \quad \Psi_2 = |dead>$$

The total wave function *before* you open the box is:

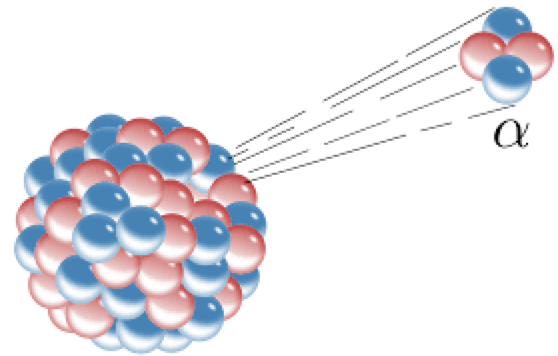
$$\Psi = a \cdot \Psi_1 + b \cdot \Psi_2 = a \cdot |alive> + b \cdot |dead>$$

Before box is opened, the cat is neither alive nor dead!

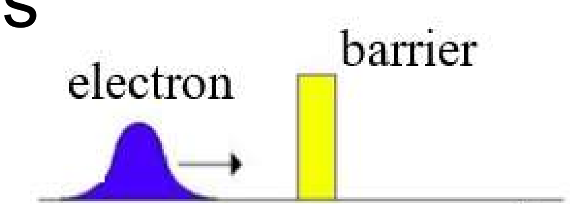
Opening the box is an observation, which collapses the cat's wave function, and *makes the cat alive or dead.*

quantum tunneling

Ex. Alpha particles are made up of 2 protons and 2 neutrons. These particles have a small probability of being found outside the nucleus. So, sometimes they "tunnel out."



Ex. When a electron approaches a barrier, its Y extends through the barrier—it has a small probability of being found on the other side. It can tunnel through.



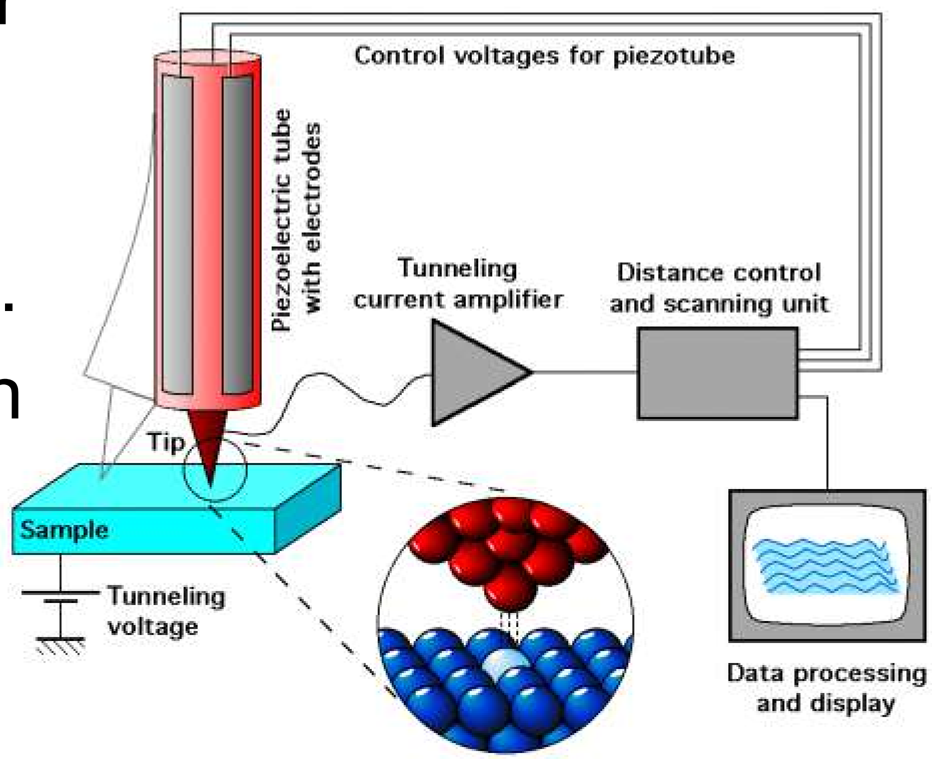
So they sometimes are found on the other side!

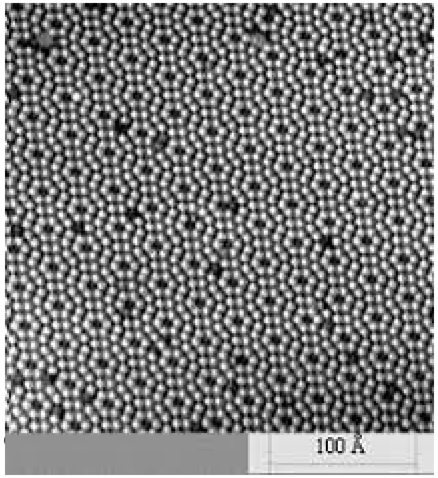
Electron scanning tunneling microscope:

Bring tip of microscope near to the surface of a sample.

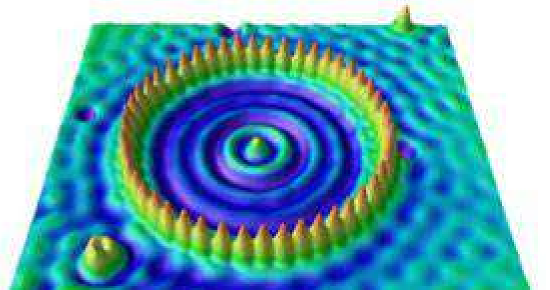
Electrons tunnel from sample to tip of microscope.

More tunneling occurs when tip is closer. More current means surface is closer.





You can see images of individual atoms!



Quantum computing

- A classical **bit** of information can be either 0 or 1.

- A quantum bit, or **qubit**, can be in a 0 or 1 quantum state, or in a superposition of the 1 and 0 states.

Classical Bit

When it is measured, however, it is always 0 or 1.

The probability of either outcomes depends on the qubit's quantum state immediately prior to measurement.

- **Correspondence principle**

First stated by Niels Bohr says:

"If a new theory is valid, it must account for the verified results of the old theory."

Bohr said that calculations using the quantum theory must *correspond to* classical physics (laws for large objects in the "normal world") in order to be valid.

→ *Correspond to* here means: overlap with, agree with, give the same, successful results

– Does quantum correspond to classical? Yes!

– Although valid, is it *useful* to apply quantum theory to huge object like a planet?

– No, even though it gives the same results.

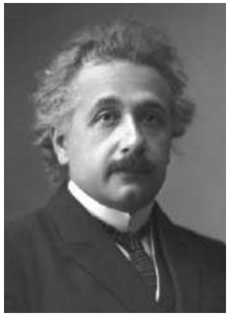
Classwork

19. Exactly what is it that "corresponds" in the correspondence principle?

20. Would Schrödinger's equation be valid if applied to the solar system? Would it be useful?

Example of the Correspondence Principle

For over 100 years, Newton's theory of gravity was successfully applied to the motions of planets, stars and rockets: *Gravity is a force*.



In 1916, Einstein proposed his *General Theory of Relativity—a* new way in which gravity works: *Gravity is the curvature of space time.*

Einstein's theory gave the same results as Newton's theory for "everyday" gravity…it *corresponded to* the old theory there.

But the new theory gave improved results when applied to "extreme" gravity: black holes, the expanding universe, gravitational lensing, etc.

Correspondence Principle
CHECK YOUR NEIGHBOR

To which of these does the correspondence principle apply?

A. The Schrödinger equation leads to Newton's equations for orbital motion of satellites.
B. The energy of a particle can be expressed as $E = mc^2$.
C. Diffraction can be explained with either particles or photons.
D. All of the above.

Correspondence Principle
CHECK YOUR ANSWER

To which of these does the correspondence principle apply?

D. **All of the above.**

Explanation:

Unlike Heisenberg's uncertainty principle, the correspondence principle is a general rule. Old and new theory must overlap where both are valid.

Test Tomorrow!

On Chapters 31 and 32.

Suggestion: Read Chapter 32!