The Nature of the Electron

The Challenge of Quantum Reality

CERN HST 2023

Dave

Sean

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Black Box

Building and Revising Scientific Models

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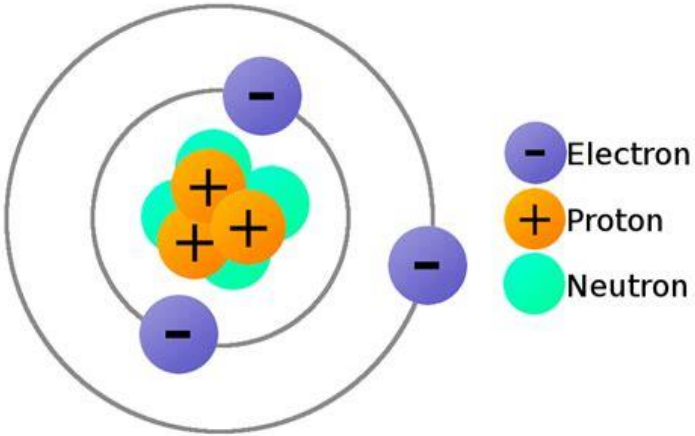
What is an electron?

an elementary particle consisting of a charge of negative electricity equal to about 1.602×10^{-19} coulomb and having a mass when at rest of about 9.109×10^{-31} kilogram or about $1/1836$ that of a proton



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Predict, Observe, Explain Demonstration: Black Box

Activity 1: Video Summary
A question sheet designed to encourage student dialogue.

Activity 2: Further Investigation of Wave-Particle Duality
This question sheet allows the student to dig a little deeper into the material both numerically and conceptually.

Activity 3: Advanced Mathematical Analysis
An enrichment activity that goes beyond the standard high school curriculum but is within the ability of stronger students.

Activity 4: Investigating the Nature of the Electron
An authentic, hands-on, discovery learning activity where students will use the double-slit experiment to investigate the nature of classical particles, classical waves, light, and electrons.

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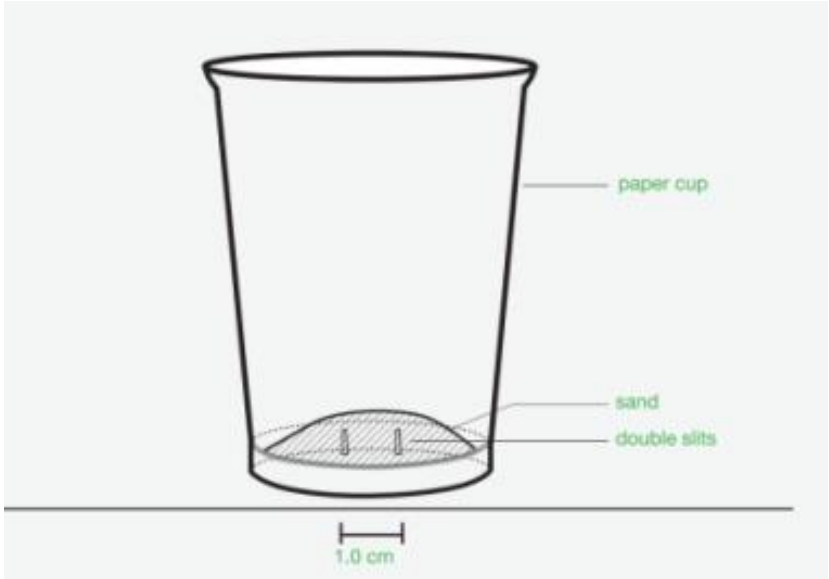
Double-slit Experiment with **Classical Particles**

Predict what pattern the sand will make on the paper.

Explain your prediction.



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Double-slit Experiment with **Classical Particles**

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Double-slit Experiment with **Classical Particles**

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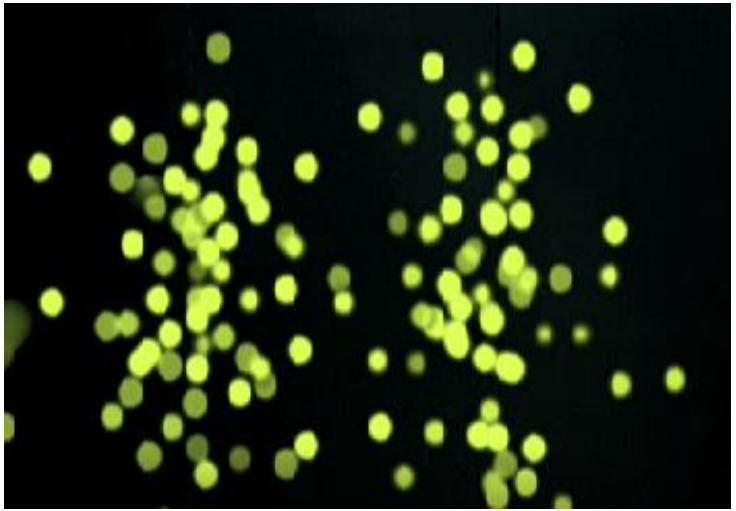
Particle Model

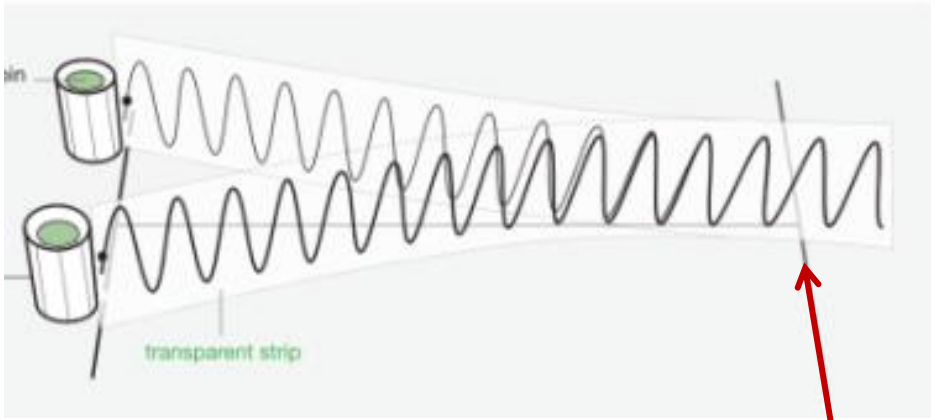
- Localized object
- Only in one place at one time
- Only one can be in a location at a time



Double-Slit Experiment with **Classical Waves**

Predict what pattern you will observe along the line.

Explain your prediction.



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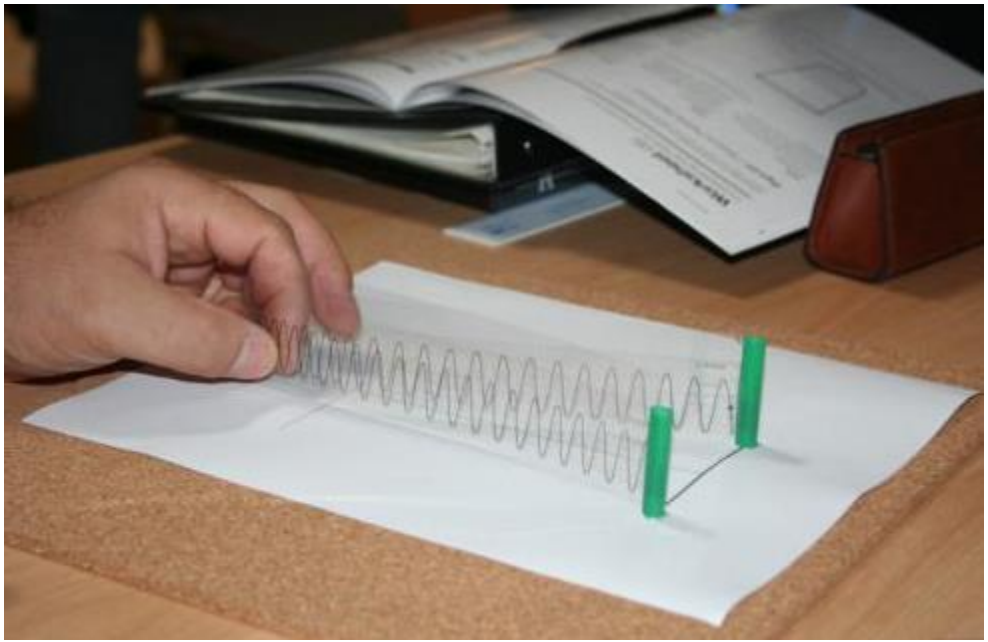
Double-Slit Experiment with **Classical Waves**



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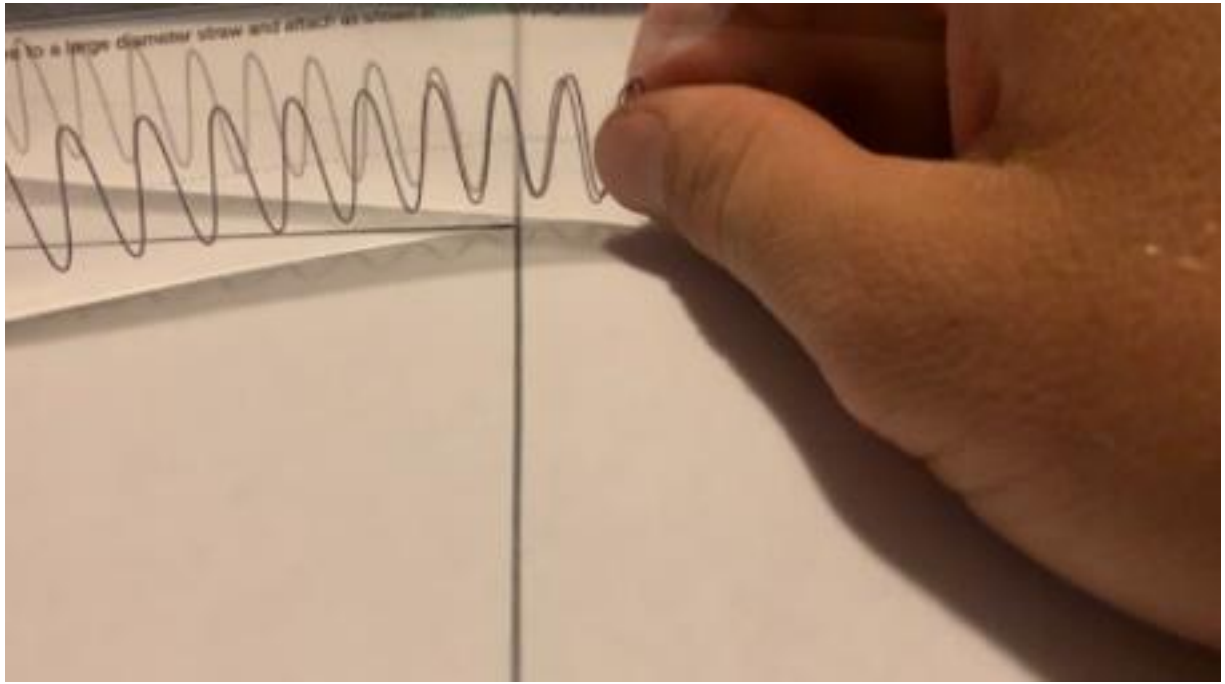
Double-Slit Experiment with **Classical Waves**



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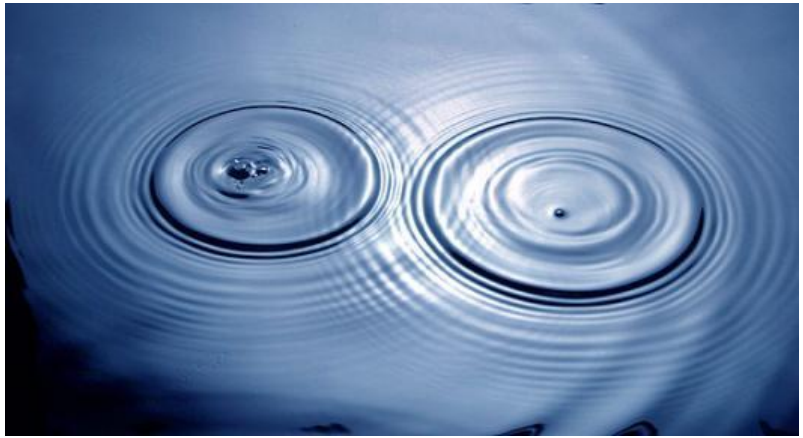
Wave Model

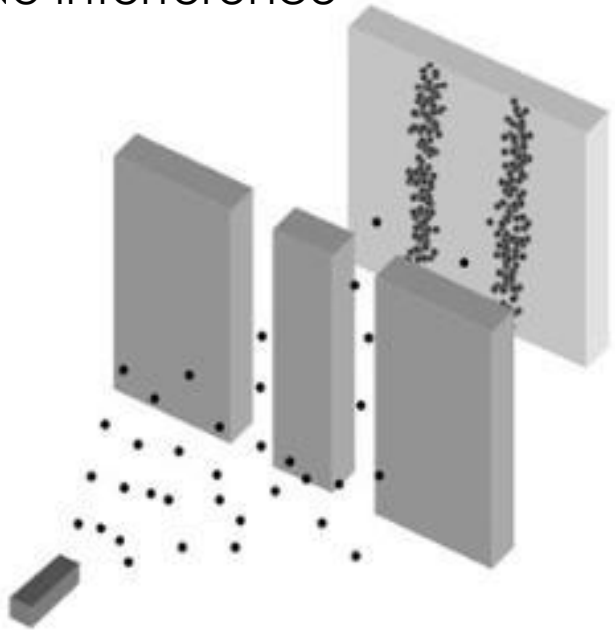
- Non-localized
- Spread out
- Add together to produce interference



Summary

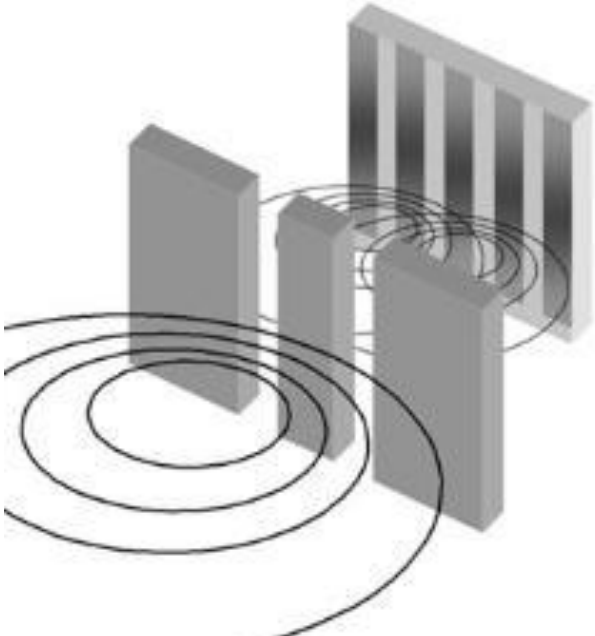
CLASSICAL PARTICLES

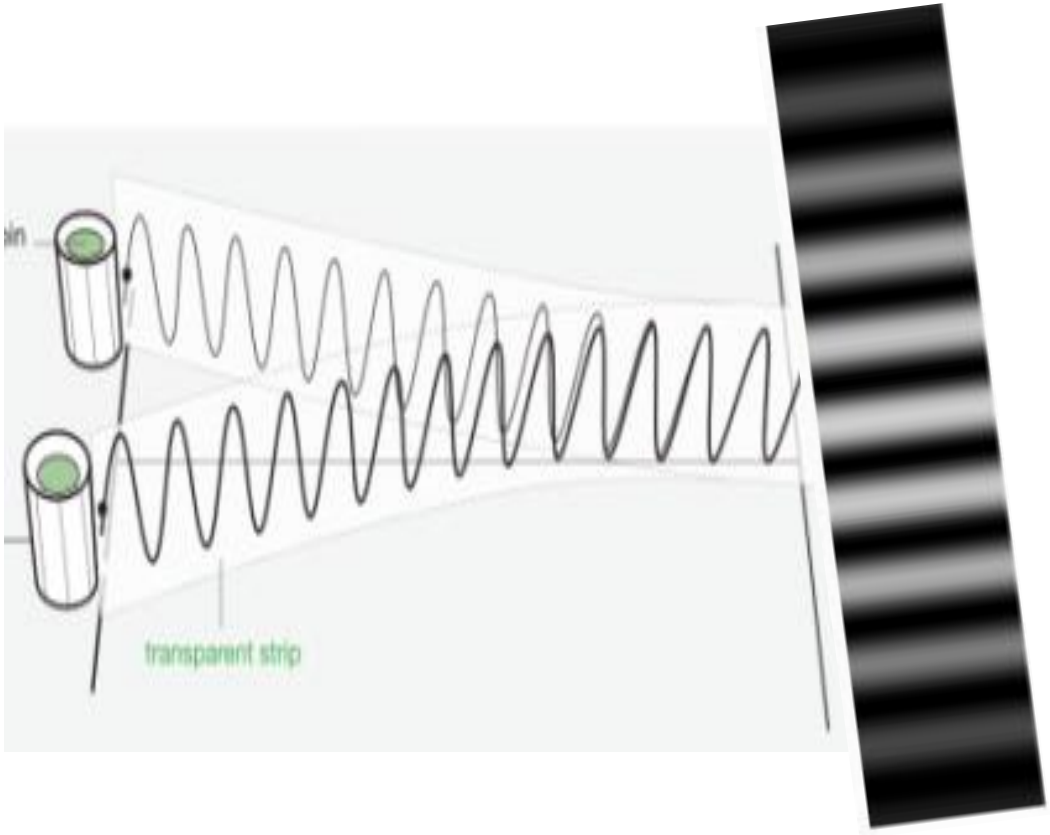
1. Localized
2. Collide with each other
3. No interference



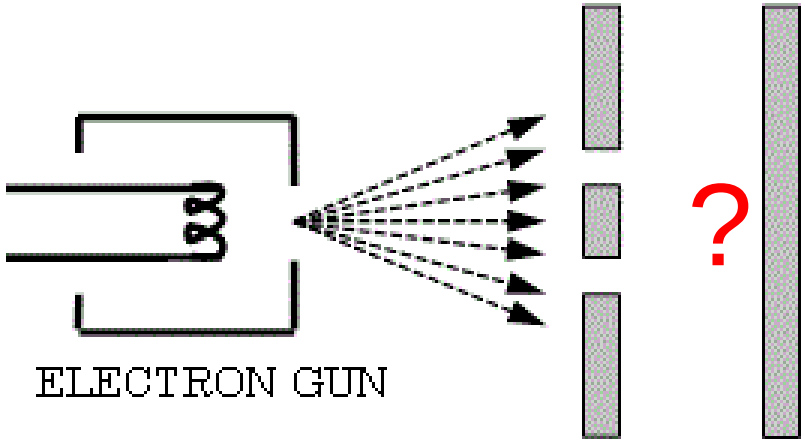
CLASSICAL WAVES

1. Spread out (non-localized)
2. Don't collide with other waves
3. Interference





What happens when electrons go through the slits?



What model will your students use?

Electron Double-slit Experiment

Download the Challenge of Quantum Reality resource and video at:
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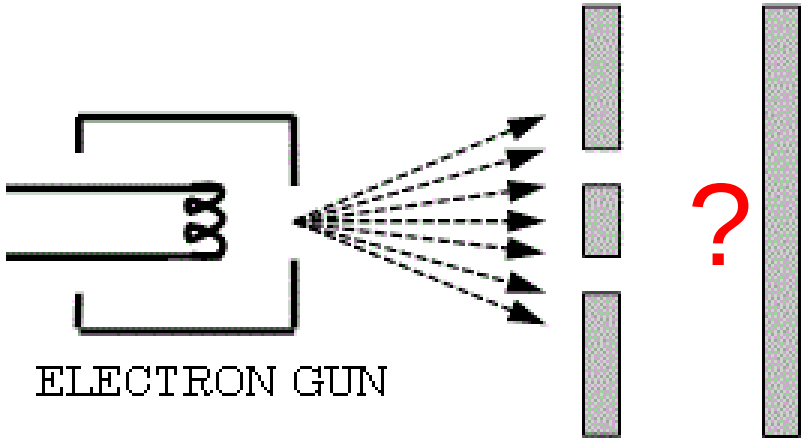
Electron Double-slit Experiment

Predict what pattern is observed on the detection screen.

Explain your prediction.



Observation

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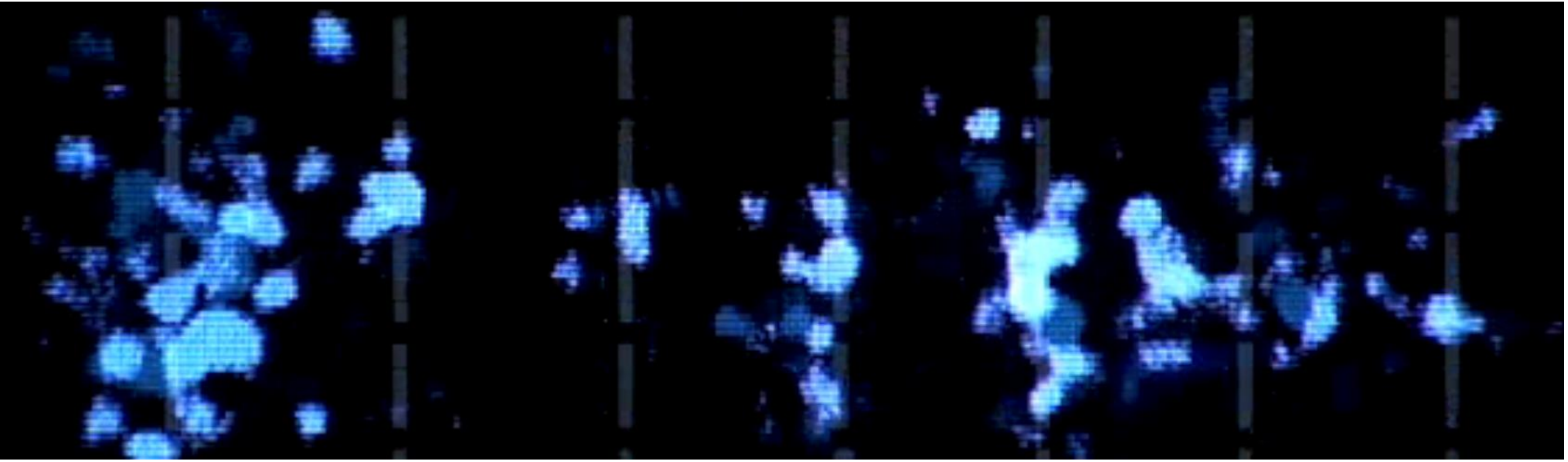
Observation



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One electron at a time

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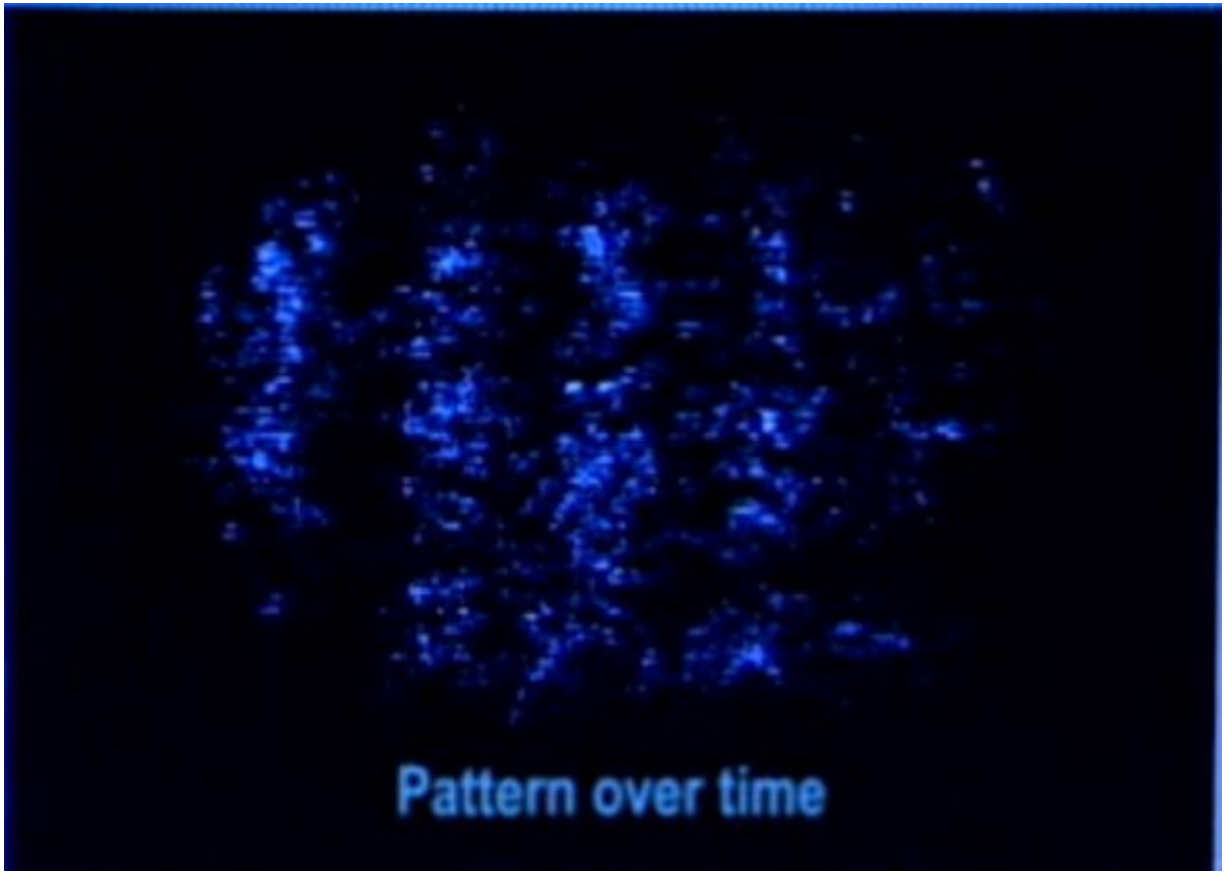
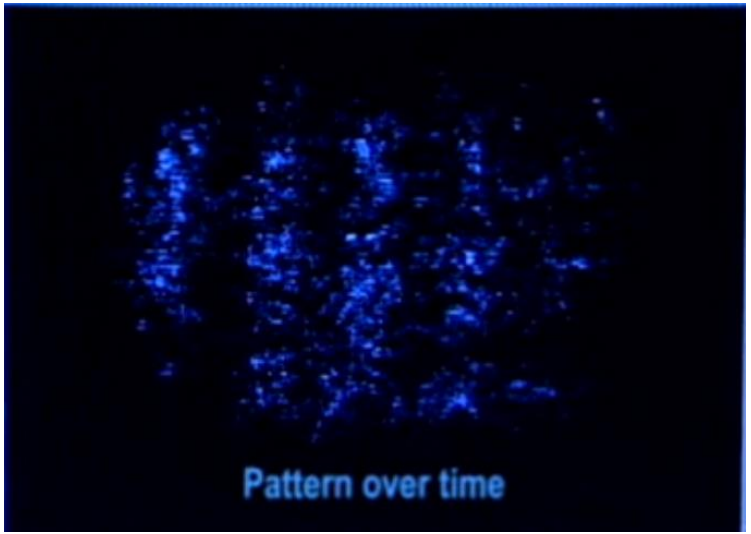


Wave-Particle Duality

- **Particle model** explains each individual electron detection.
- **Wave model** explains overall pattern



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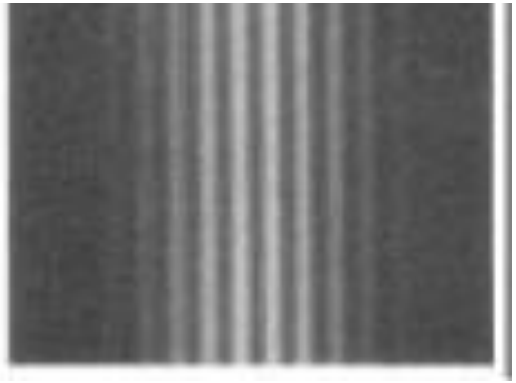
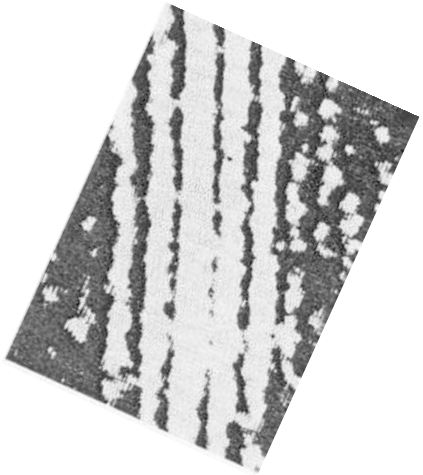
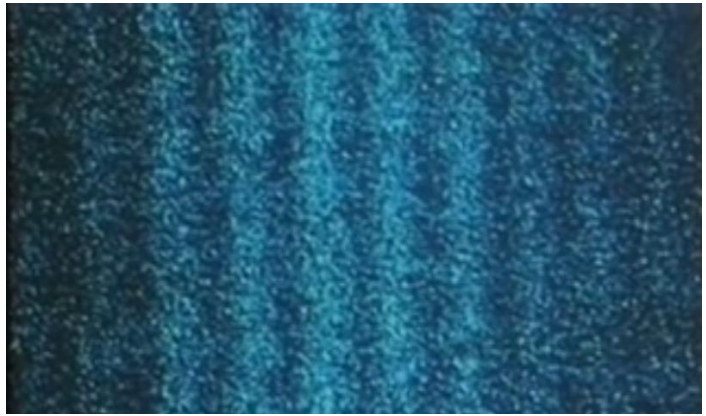
Many other experiments have observed similar results



Jönsson 1961



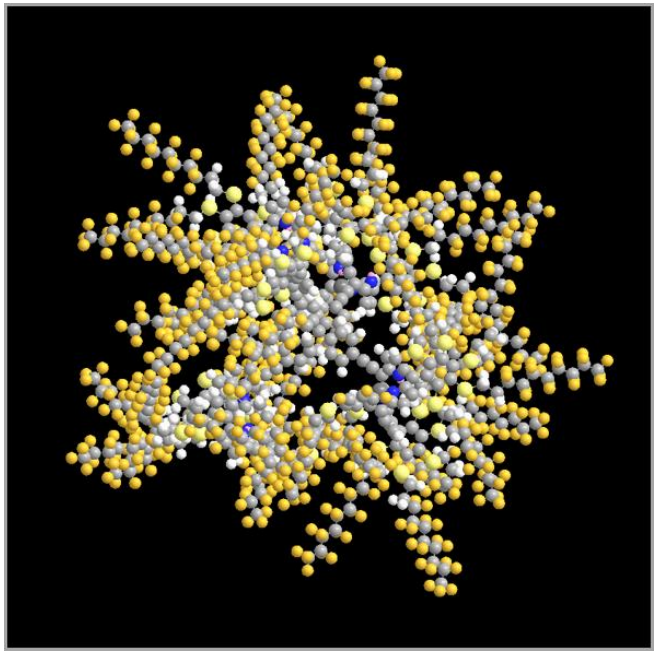
Merli et al. 1976



Tonomura et al. 1989

Wave-particle duality is widespread

- Protons
- Neutrons
- Light
- Atoms
- Molecules



$C_{707}H_{260}F_{908}N_{16}S_{53}Zn_4$
mass = 25 000 amu

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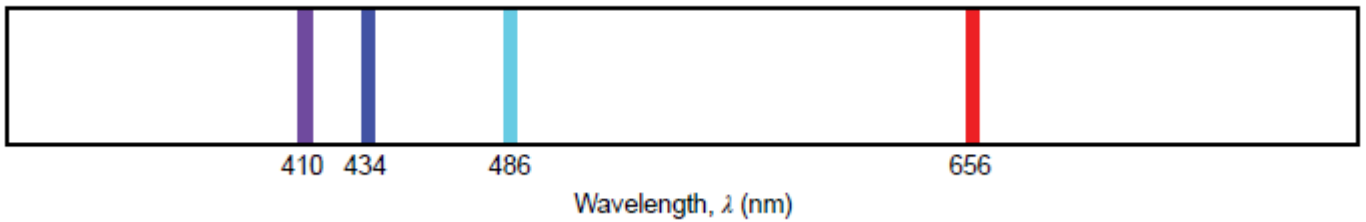
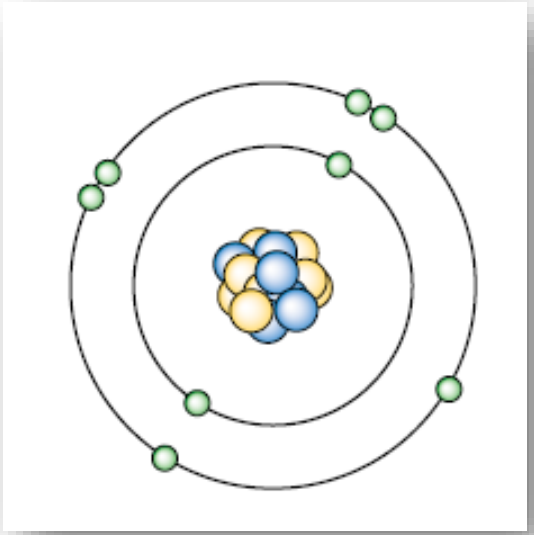
Bohr explains hydrogen spectrum using discrete energy levels for electrons



Are we creating the right images?



"We must be clear that when it comes to atoms, language can be used only as in poetry. The poet, too, is not nearly so concerned with describing facts as with creating images and establishing mental connections."

—Niels Bohr

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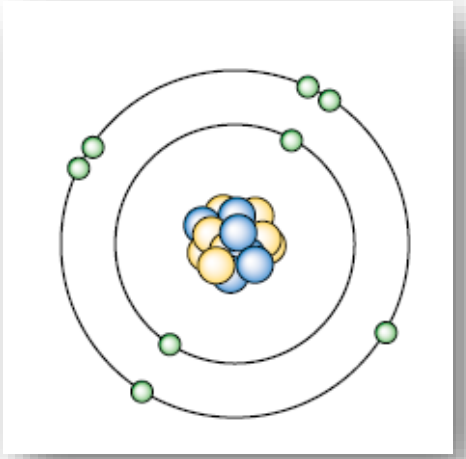
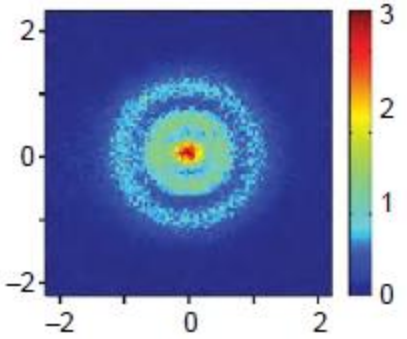
There are several problems with the Bohr semi-classical model:

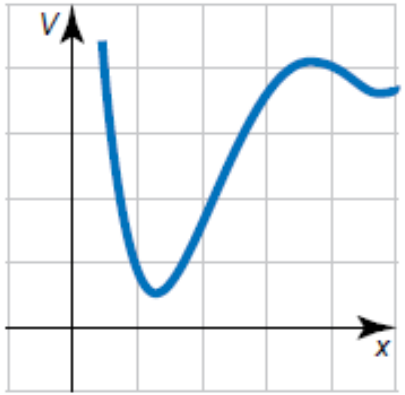
1. Zeeman effect
2. Only explains hydrogen spectrum
3. How do electrons know where to jump?
4. Can't possibly work



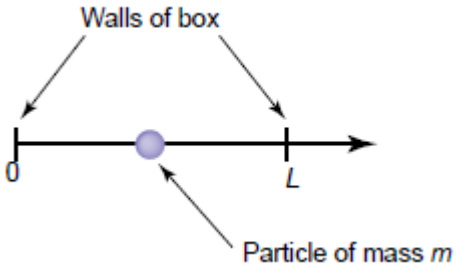
Electrons in Atoms are Bound (constrained)



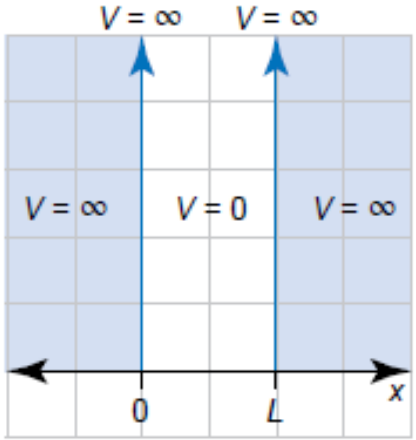
Atom



simplify



1-D box



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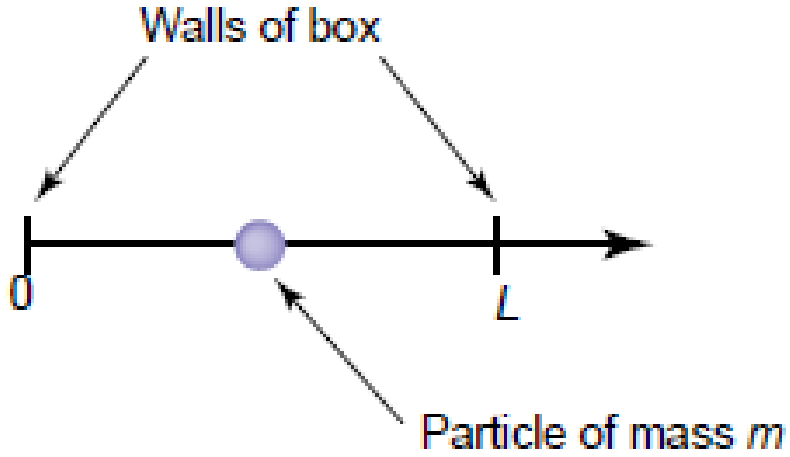
Classical Particle in a Box

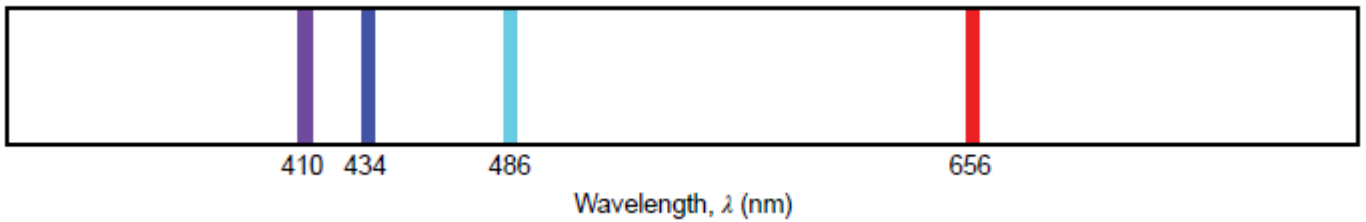
- The momentum of a particle can be expressed in terms of the kinetic energy, E and its mass, m



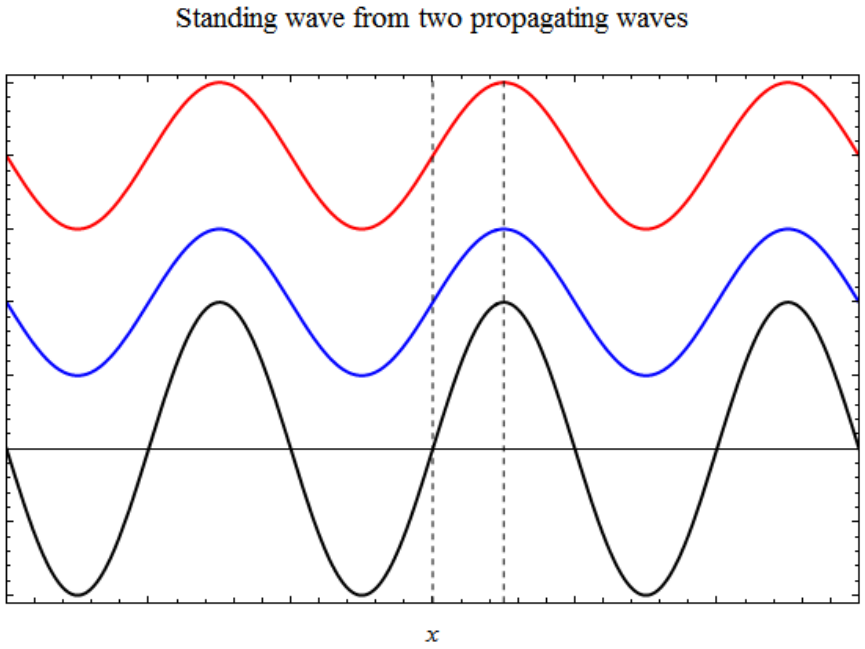
$$p = \sqrt{2mE}$$

What are the constraints on p or E?

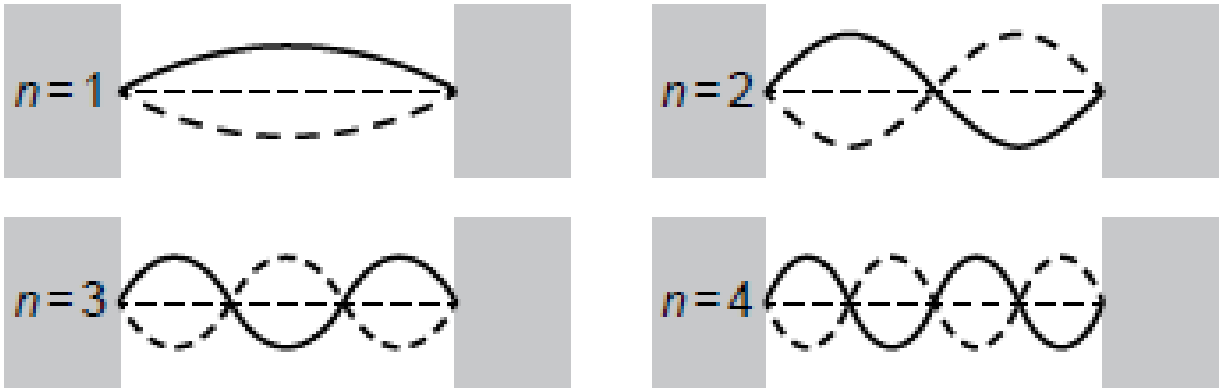
Treating the electrons as a particle model does not explain spectrum



Waves in a Box



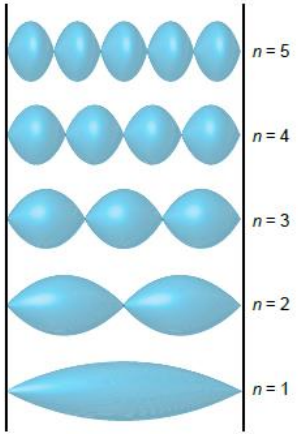
Stable configurations of Waves in a Box

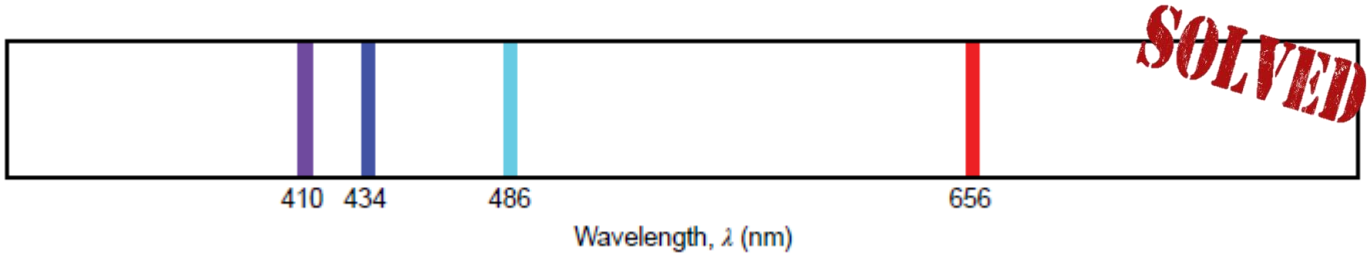


$$\lambda = \frac{2L}{n}$$

Discrete Energy Levels

$$E = \frac{n^2 h^2}{8mL^2}$$





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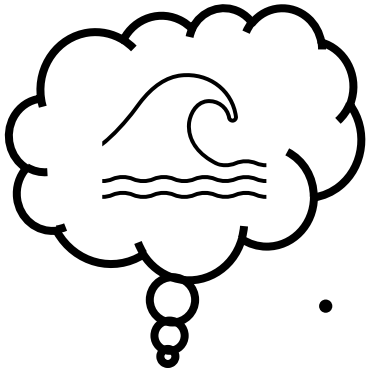
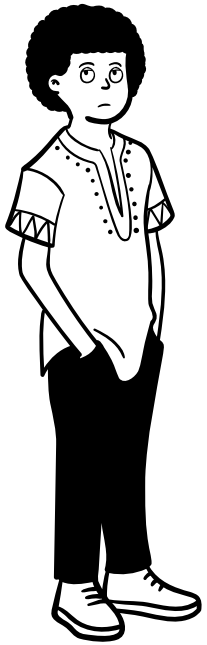


Is the electron *actually* a wave?

- What would happen to charge if it were
  like a wave?
- Waves can be partial
  and transmitted. Is
  this true for elec
- Wh
  you expect to see on the screen for a
  ectron wave striking the screen?

Electrons defy our classical models.



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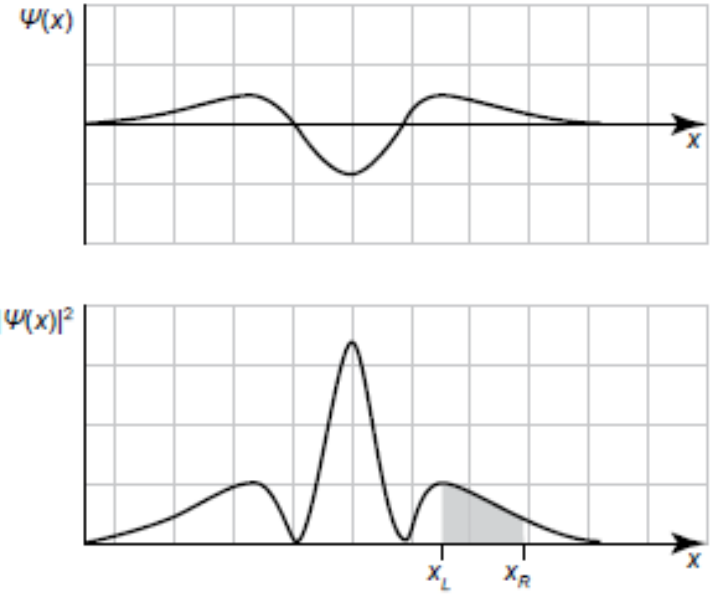
Wave Functions

- Use the mathematics of waves to describe electron behaviour
- **Probability** of detecting the electron as a particle is square of wave function
- Progression from de Broglie



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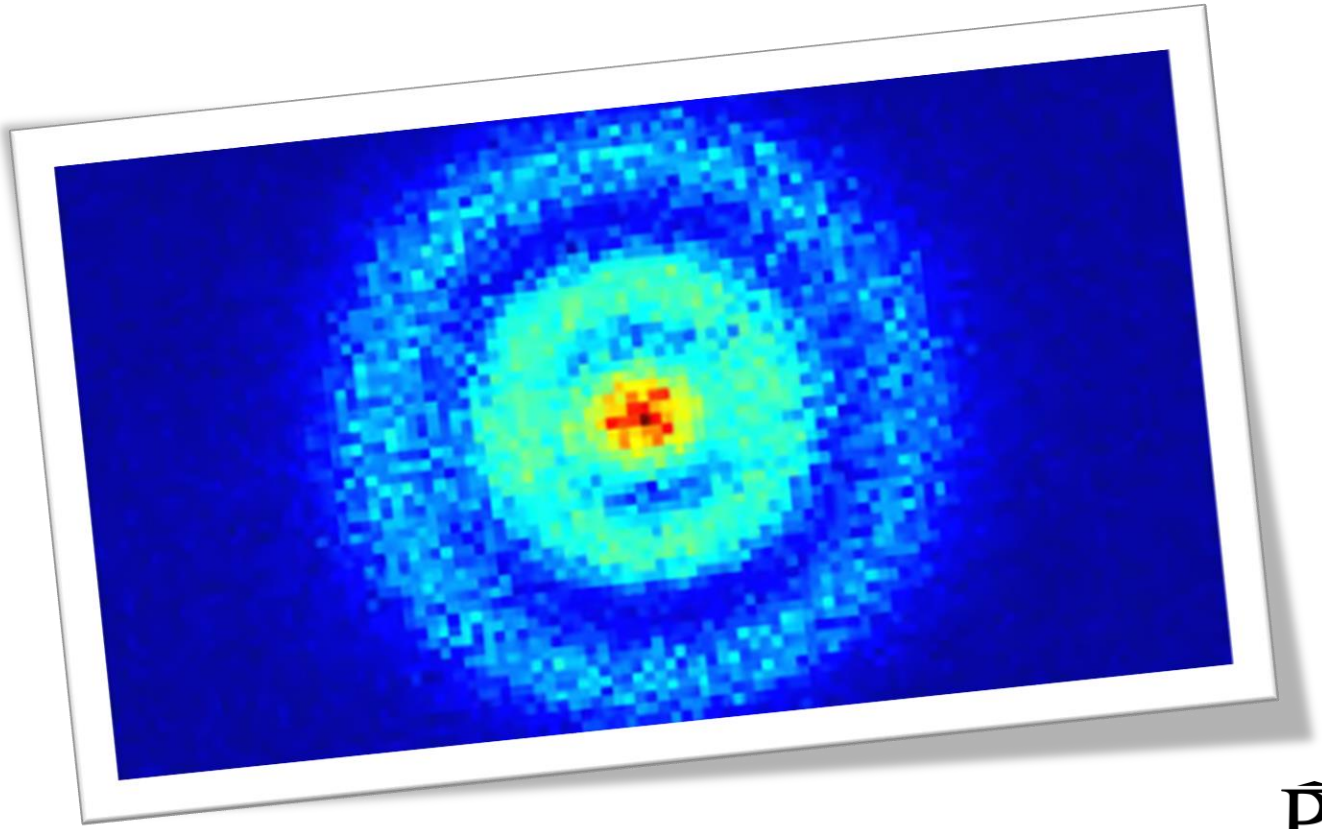
Application: Orbitals



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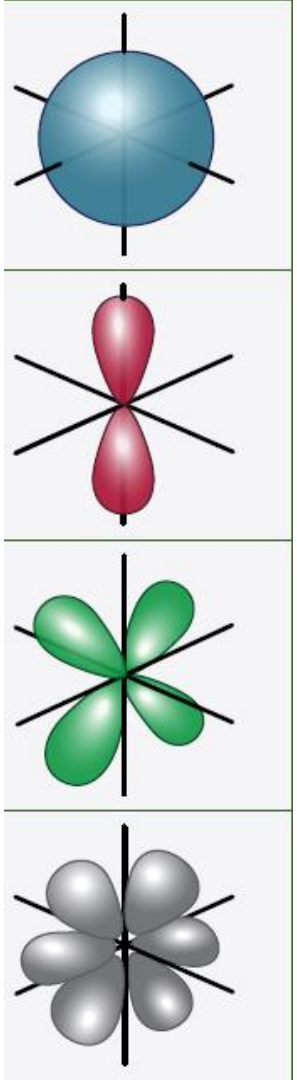

Application: Orbitals

- Orbitals are:
  - regions where the probability of detecting an electron is high
  - described by wave functions
  - a consequence of the wave-like properties of electrons

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Wave Template

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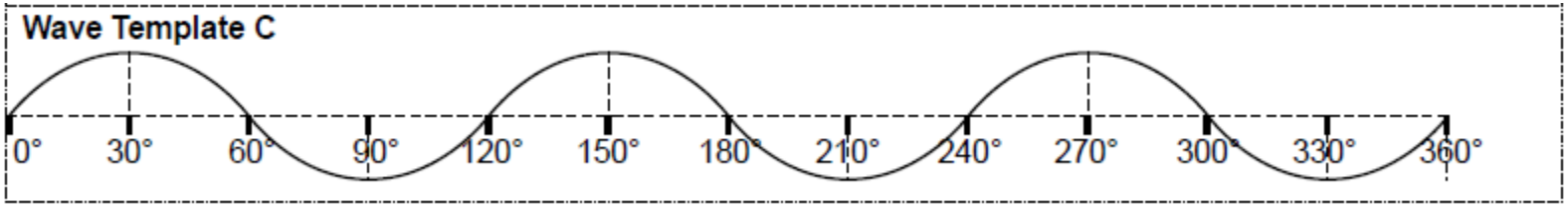
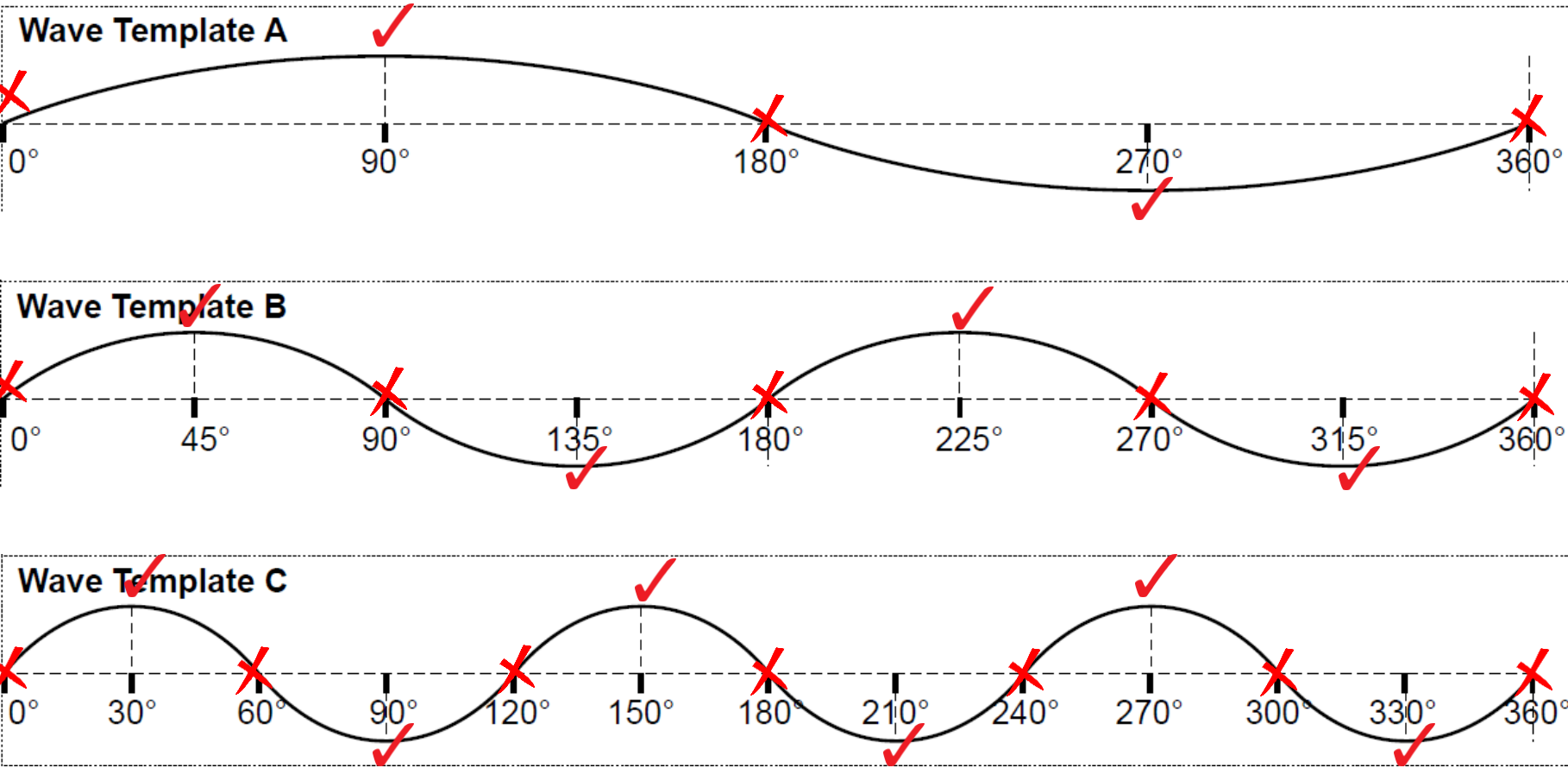
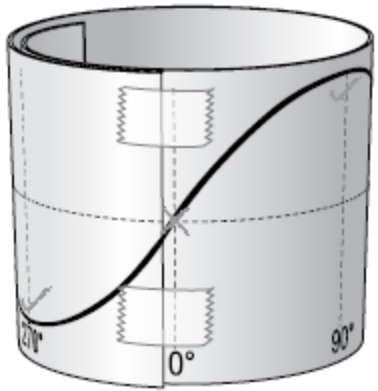


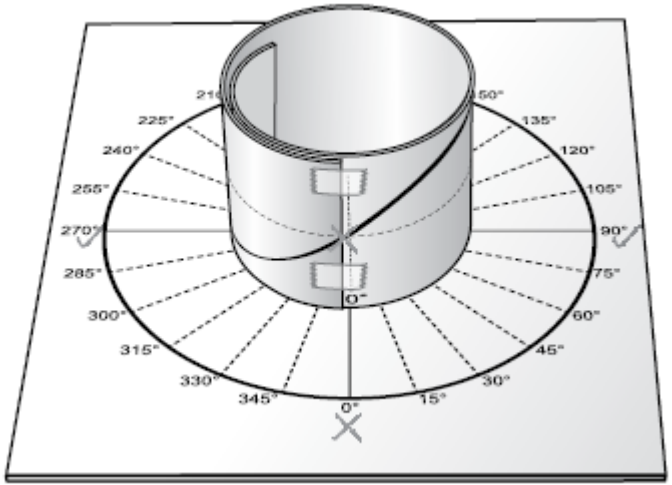
✓ Mark locations where the probability of detecting an electron is highest

✗ Mark locations where the probability of detecting an electron is lowest



Line up on Circular Graph





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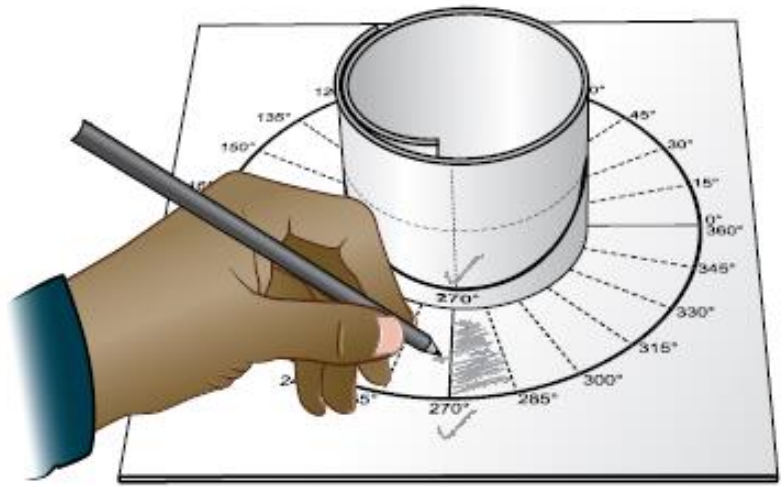
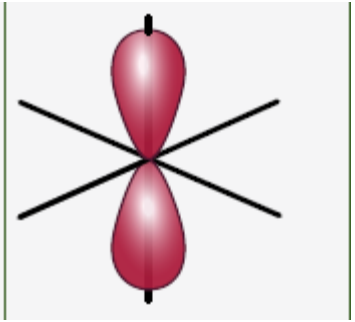
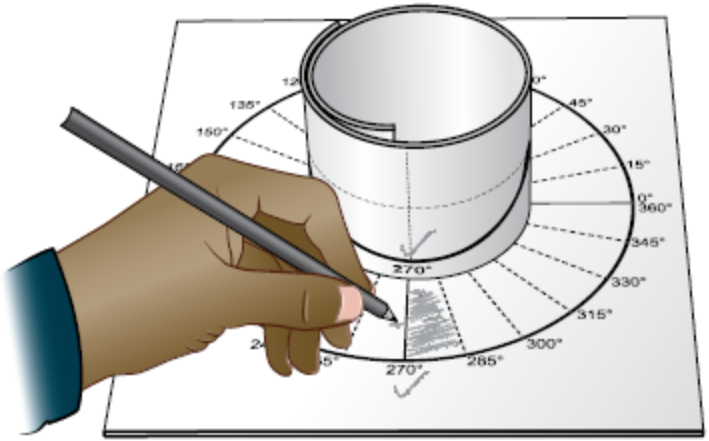
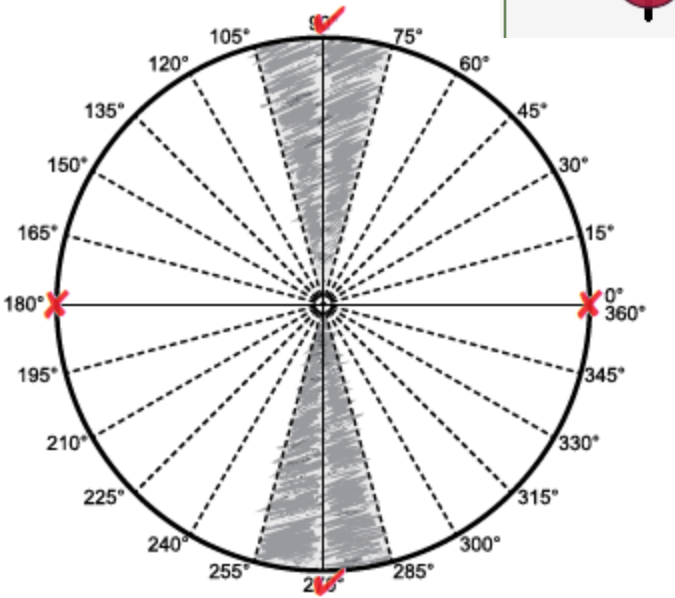
Shade in the Zones



p orbital







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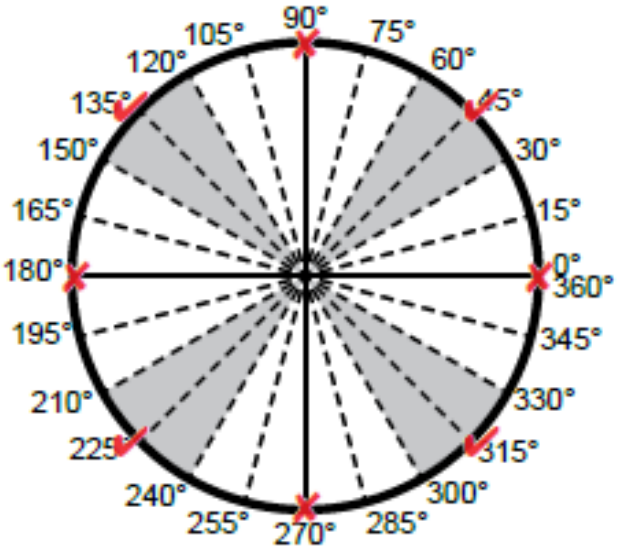
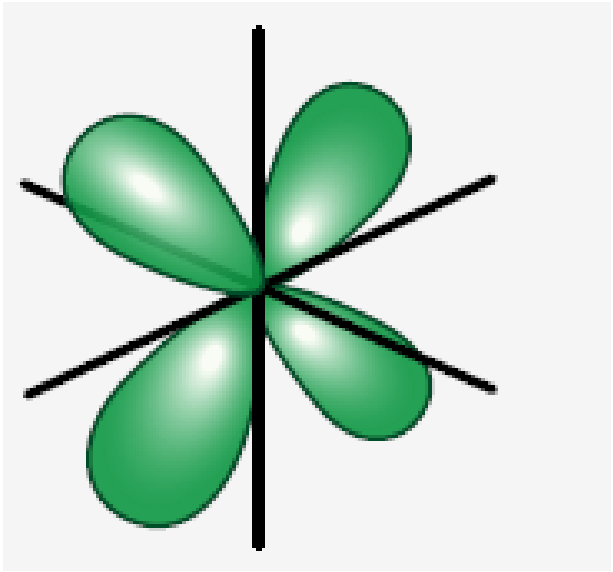
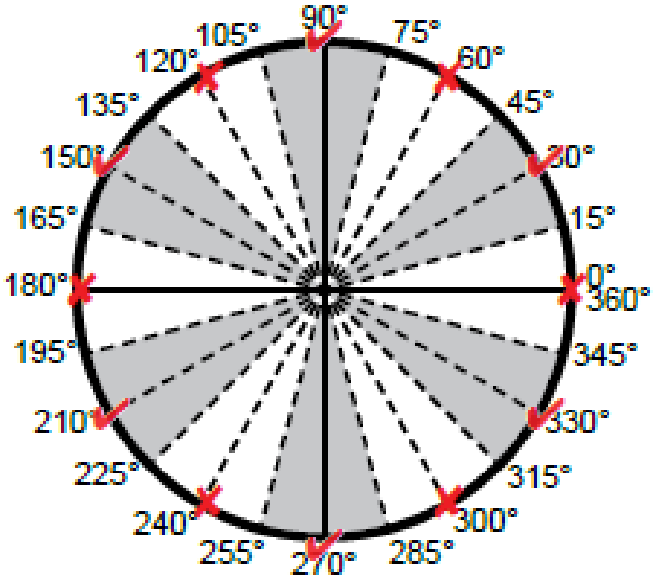
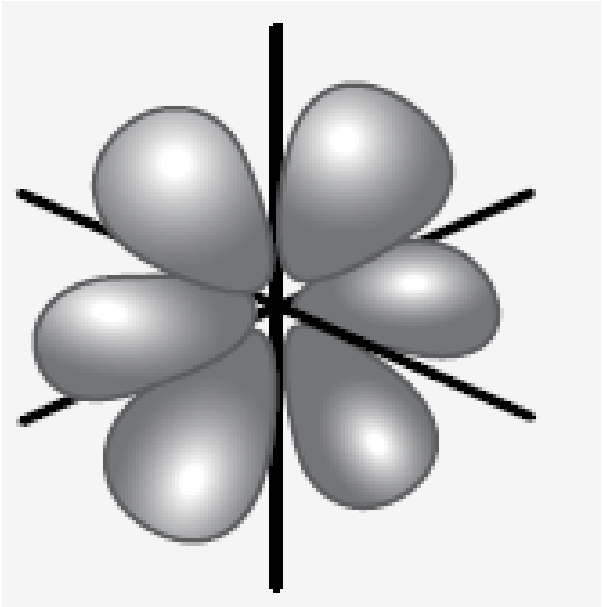
d orbital





f orbital





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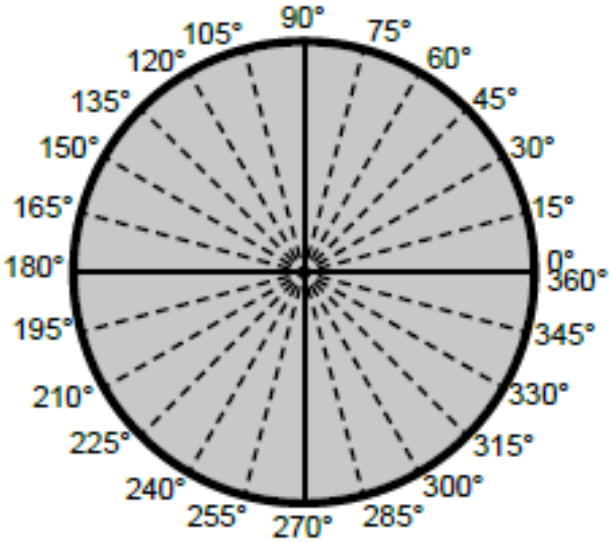
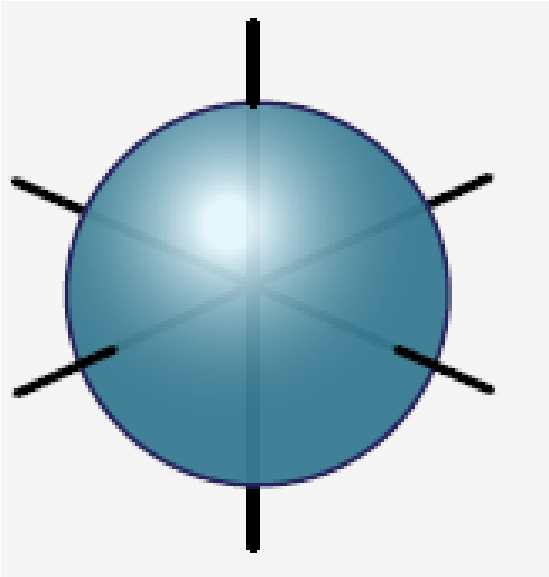
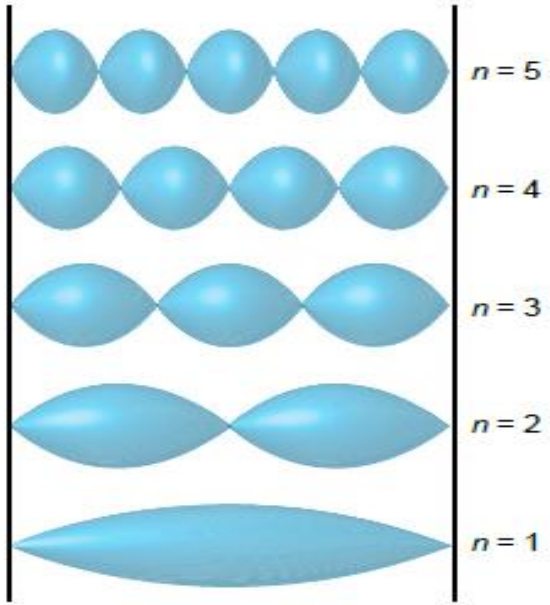
s orbital





Summary:
Wave model provides a natural explanation for discrete energy levels



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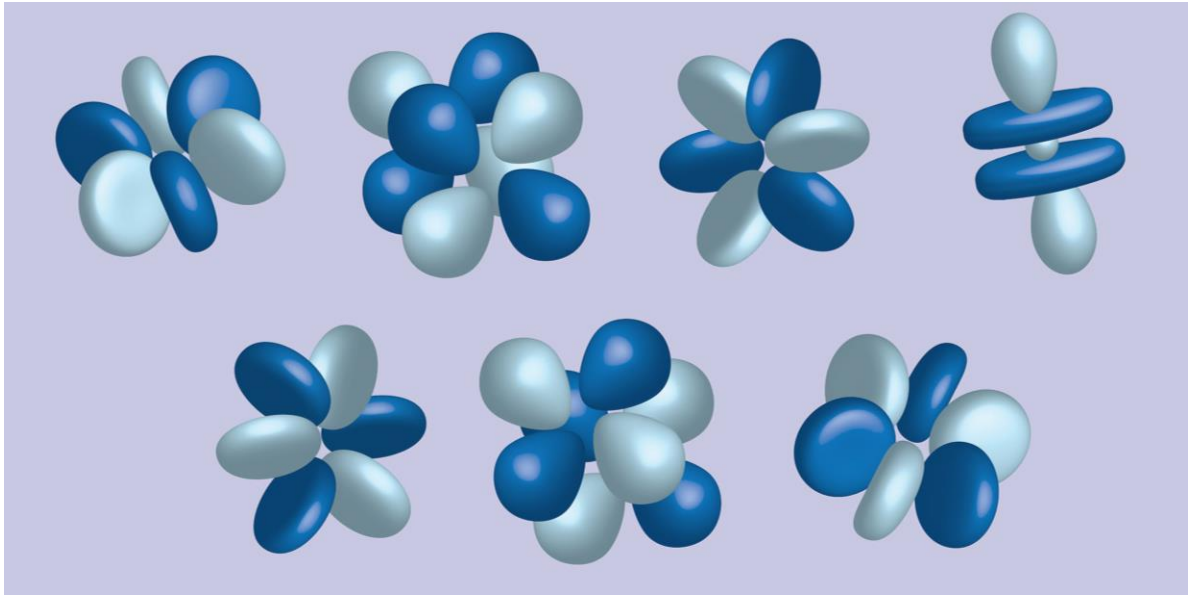
Summary:

Wave model provides a natural explanation for orbitals



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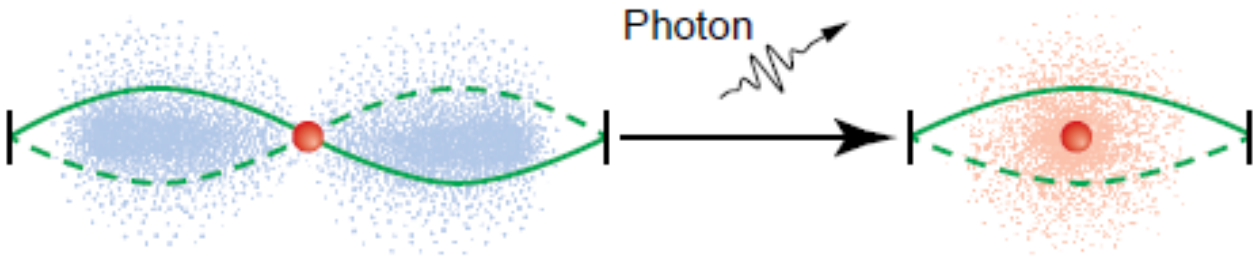
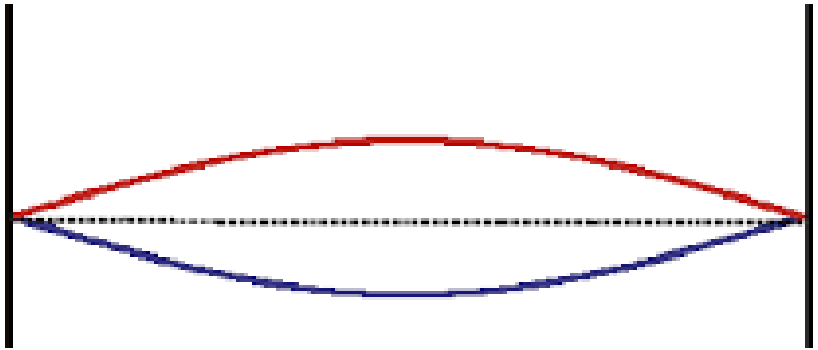
Summary:
Wave model also addresses the problem of "jumping" or "orbiting"



Summary:
Wave model also addresses the problem of non-zero lowest energy



For this resource and many others, go to:

resources.perimeterinstitute.ca

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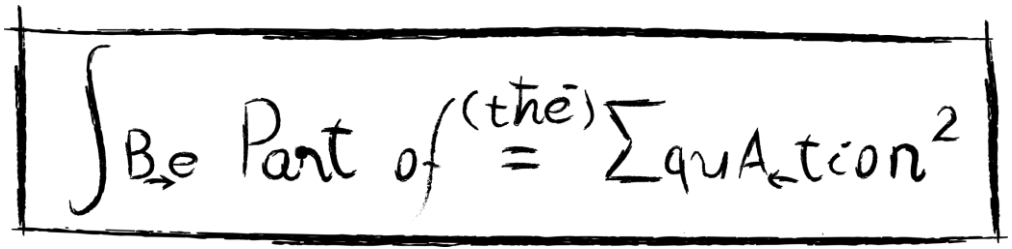
Thank You!

Want to know more about our teacher network?

Contact Emma Nichols:
enichols@pitp.ca



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Thank You!

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