

Quantum for ALL!

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Materials developed by Quantum for All

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NSF #2009351 DRK12 (*Quantum for All Conference*)

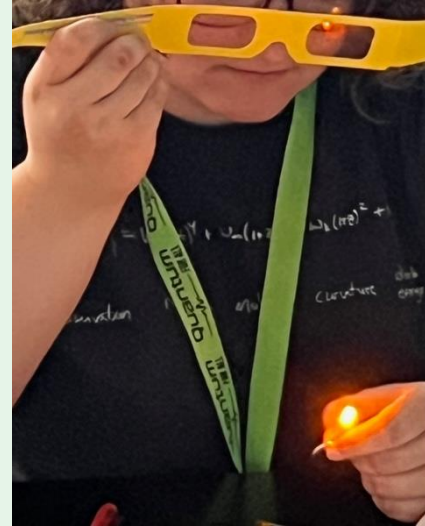
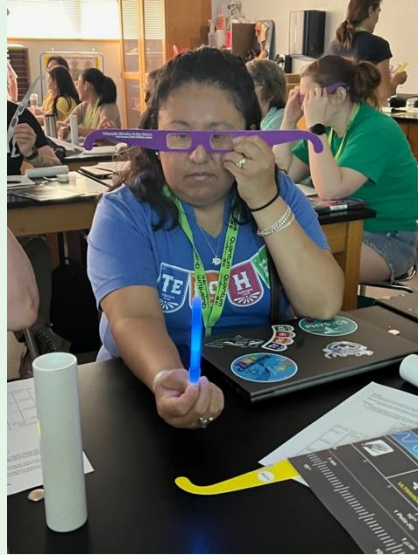
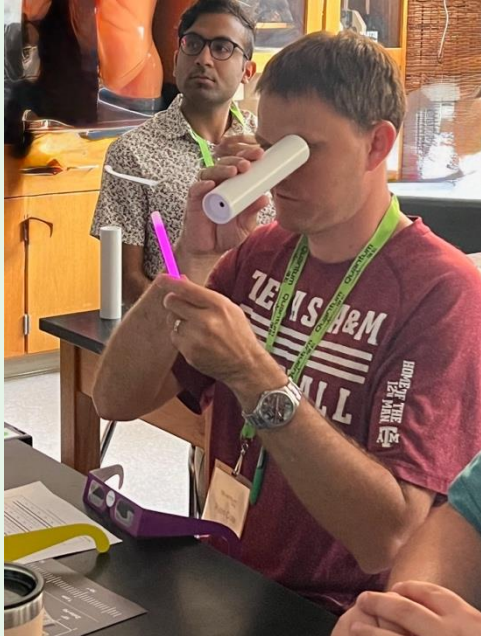
NSF #2048961 DRL (*Preparing Secondary Teachers and Students for Quantum Information Science*)



Atomic Model

Phenomena

View room lights, LEDs, and glow sticks using diffraction glasses.
Share and explain observations with peers.



Historical Perspective

- Unpicturing Atoms (Perimeter Institute Resources for Teachers)
<https://youtu.be/RuQDbl8PoJs?si=vj2RoDUY3nKQgwLV>
- Model cannot be a planetary model
 - The atoms would collapse due to accelerating electric charges emitting electromagnetic radiation. Changing electric fields induce magnetic fields. Electron would spiral into the nucleus in less than a nanosecond.
- Bohr proposed semi-classical model
 - Had hoc rule where electron was only allowed to orbit the atoms with specific values of angular momentum. But this was still treating electron as a classical particle.
- Angular momentum could only be a multiple of Planck's constant (h)
 - This restriction produced discrete energy levels which matched the spectral lines for hydrogen.

Issues with the model

- Classical particles radiate energy (ad hoc nature of rule avoided concerns)
 - Wave function has stable configurations
- How does electron know where to jump when moving from one orbit to another?
 - In quantum model they transition; changing the harmonic of the wave function.
- If electron generates a magnetic moment (by spinning) it would have infinite possible spin directions.
 - Observations show only 2 choices
 - If spinning particle the surface would have to move faster than speed of light to generate magnetic moment.
- Ionization energies predicted were incorrect
- The model did not fit the spectra for atoms with more than 1 electron.
- Although it may have exhibited wave-like behavior, it could not BE a physical wave.

Even Bohr knew the model did not work.

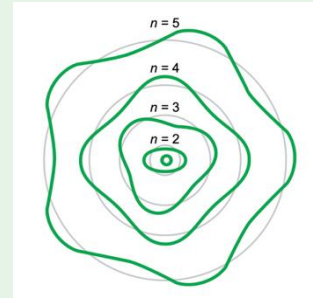
Discussions shifted from what the electron “is” to what is observed.



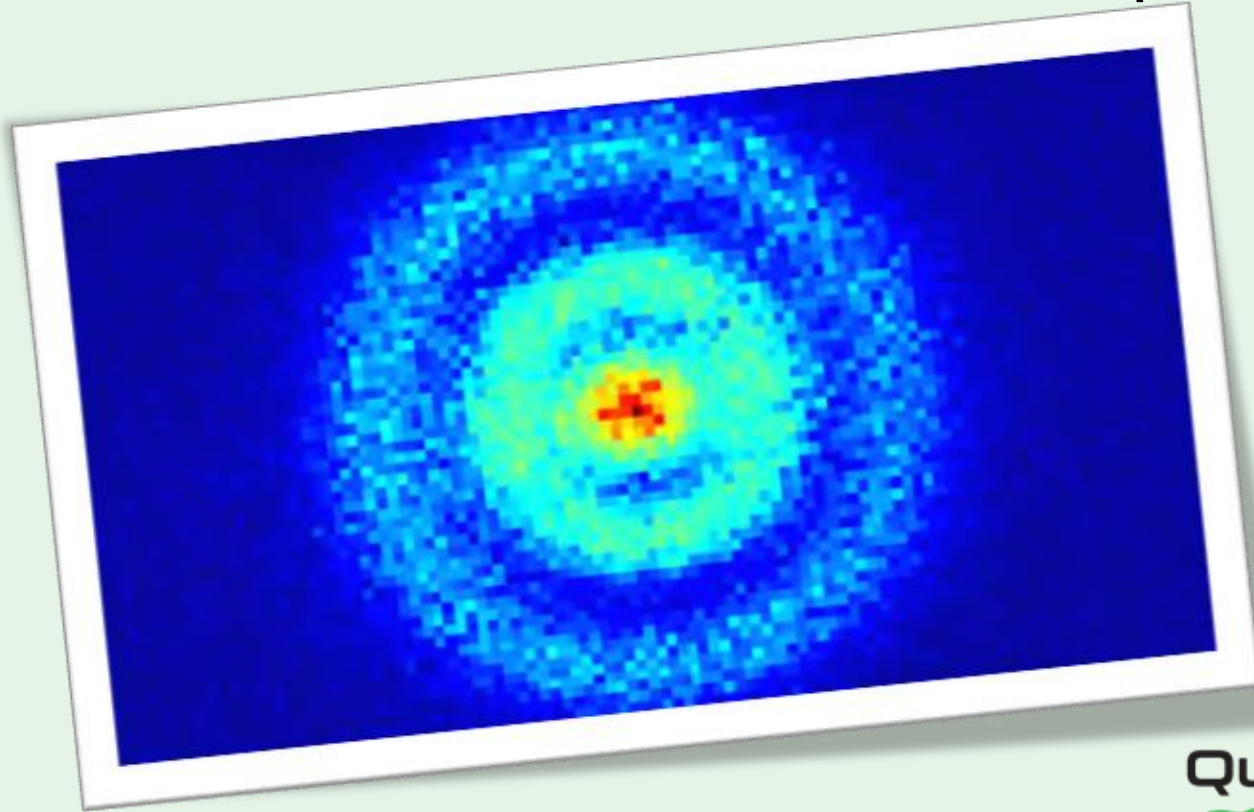
Potential Solutions

- Louis de Broglie proposed electrons could exhibit wave properties and that **wavelength** of an electron depended on momentum.
- Viewing the electron as a wave allowed it to be stable when the circumference of the orbit was an **integer multiple of the wavelength** associated with the electron.
- Stable states did not radiate energy.
- The description of a system of particles, such as atom, is the **wave function**.
- Are electrons actual waves? **(no)** Mathematics explains the observed behavior of electrons.

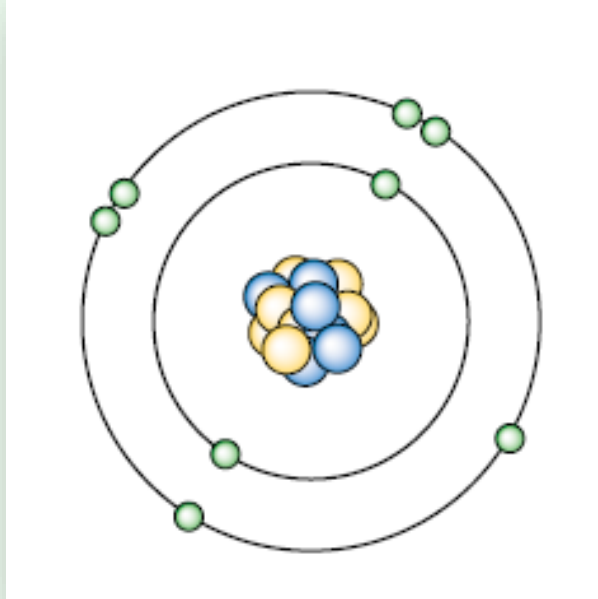
$$\lambda = \frac{h}{p},$$



The Atomic Model Based on Electron Properties



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.”

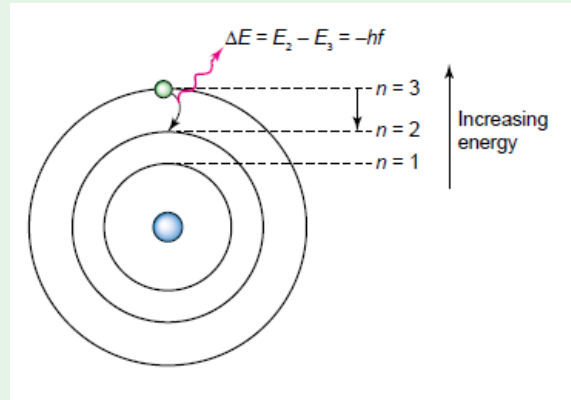
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—Niels Bohr

Bohr Model

Atoms are small things with:

- A small positive nucleus
- Electrons orbit around it in shells so only certain frequencies are absorbed and emitted



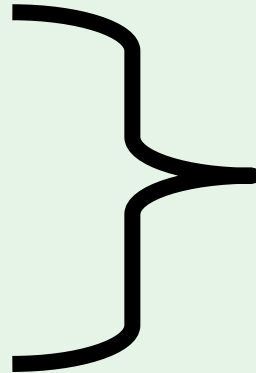
Misconceptions introduced by Bohr's Model

- Electrons do NOT:

- Orbit

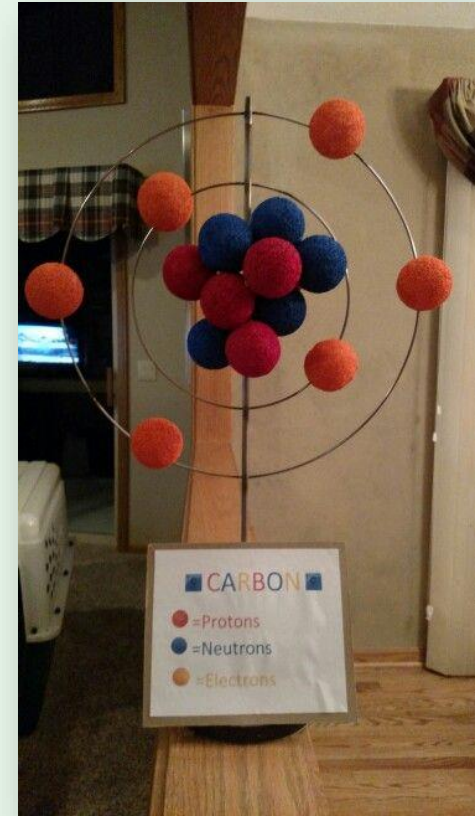
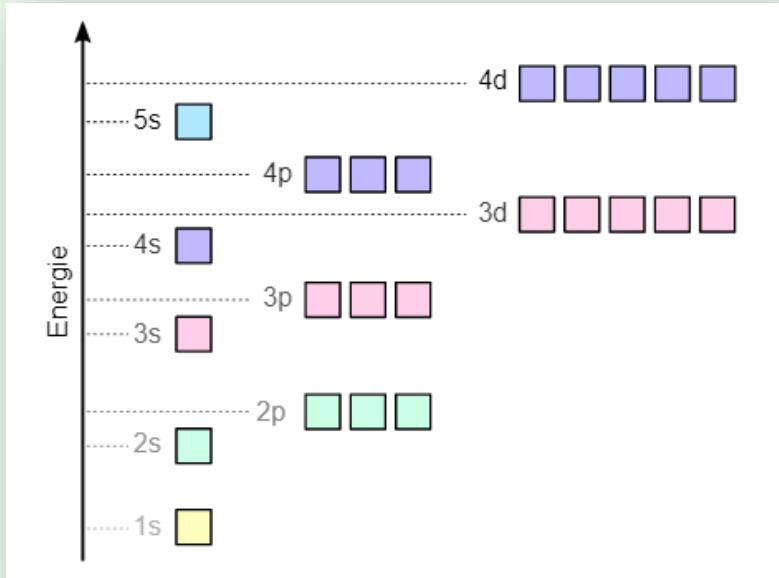
- Jump

- Spin around



Classical particle

Bohr Model



Useful bookkeeping tool, but students take this too literally!

What IS an electron?

Remember the question should not be what IS it, but what do we observe.

Typically represented as a particle, but is that what we observe?

If we send many electrons to a “screen” what would we observe? (if a particle, it would be one big blob all arriving at about the same place)

See next slides on electrons hitting fluorescent screen showing it does not behave as a classical particle. (interesting note: students are intrigued with quantum tunneling, which is not a property of a classical particle, but is important for optics and electronics. See next slide).

Sometimes they DO act like classical particles. (i.e. they can be deflected by electric and magnetic fields revealing charge and mass)

Electrons can be used to replace light in optics (i.e. microscopes) because the wavelength is shorter resulting in higher resolution.

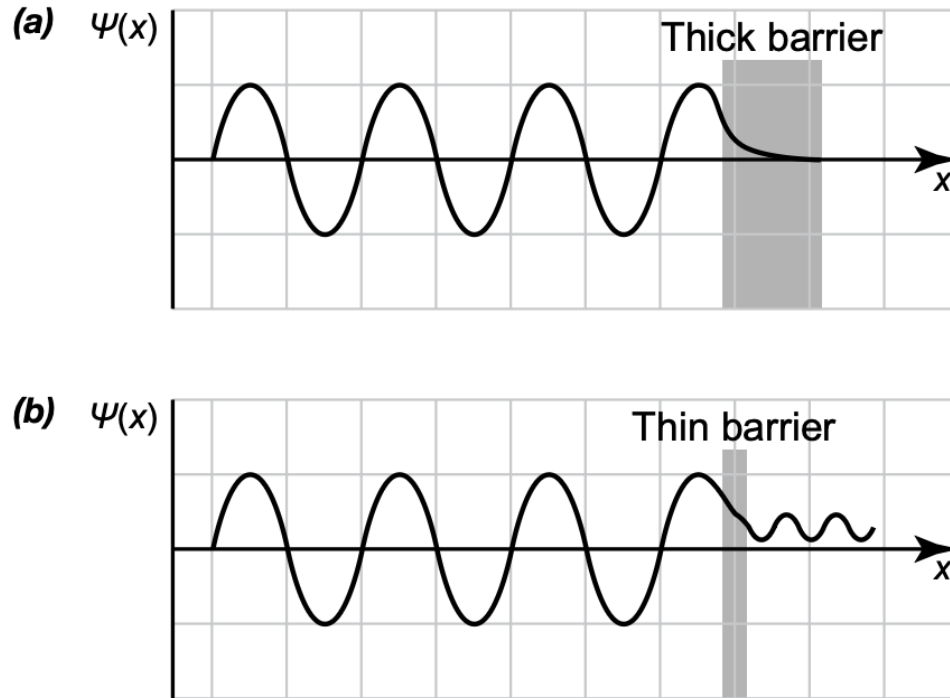
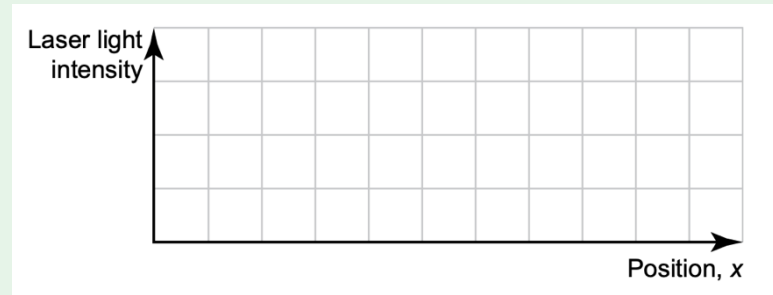
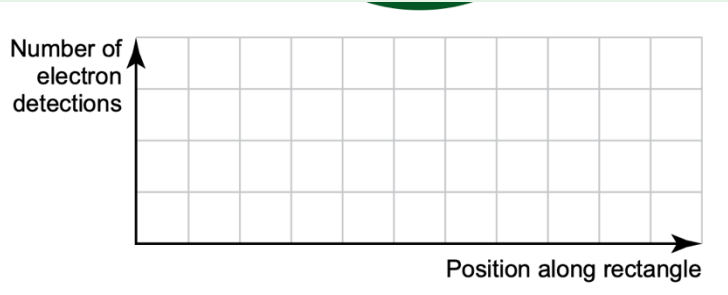
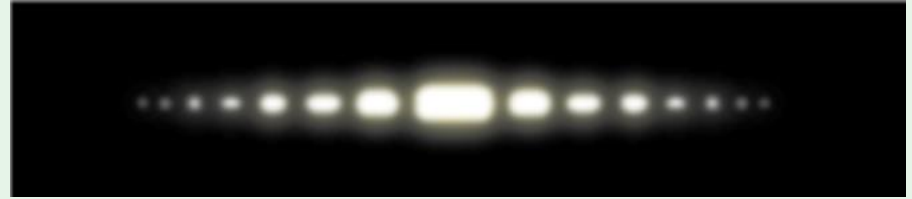
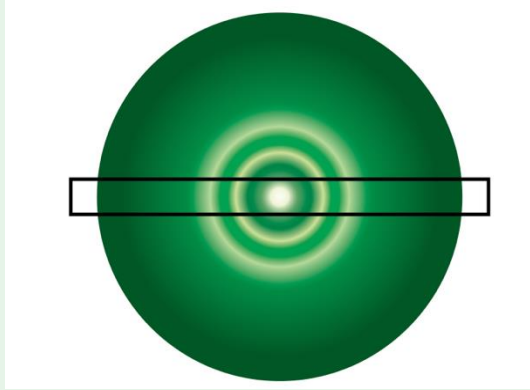


Figure 1 Unlike classical objects, quantum objects can tunnel through barriers. **(a)** If the barrier is thick, the probability is almost zero. **(b)** However, if the barrier is thin, there is a non-negligible probability that a quantum object will pass through it.

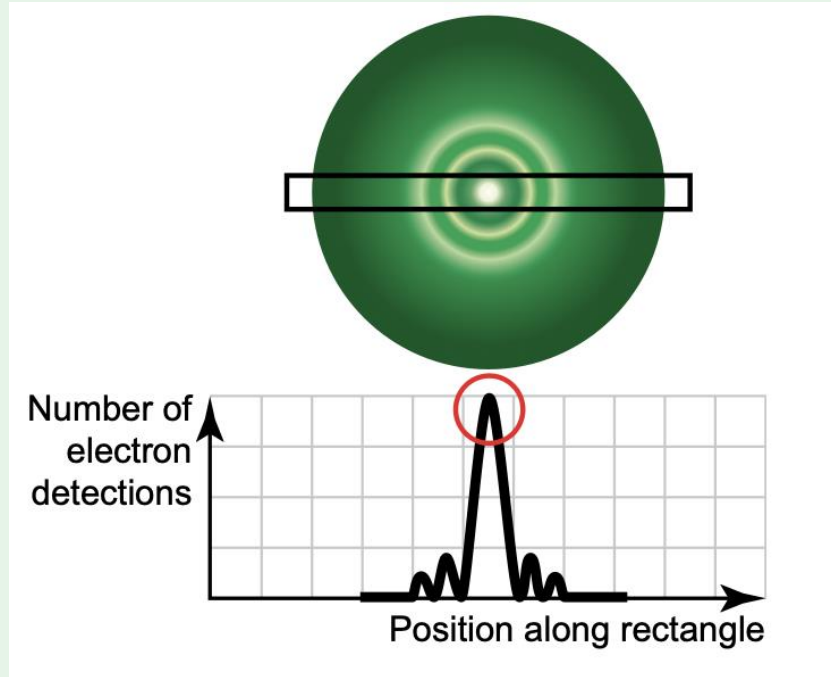
Electron “density”

TEACHER NOTE:

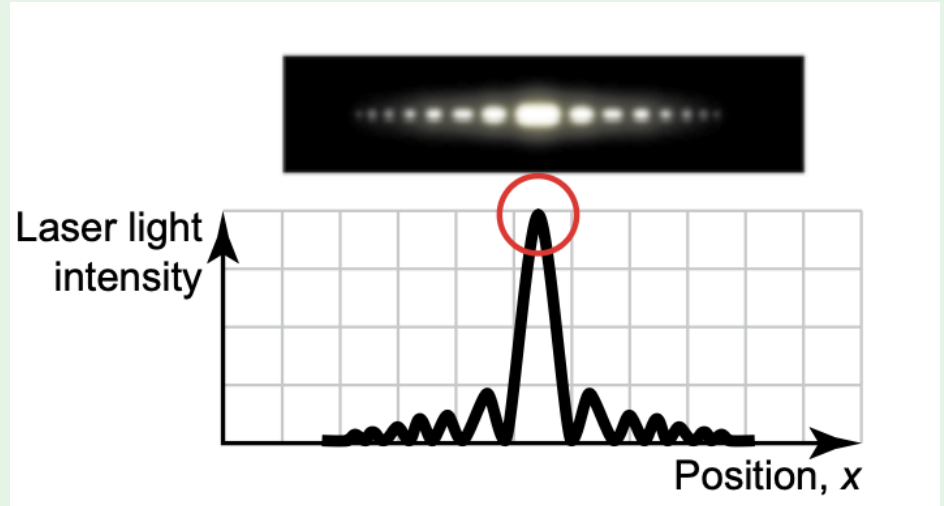
Since the graphite crystal acts like a diffraction grating, the patterns are similar



TN

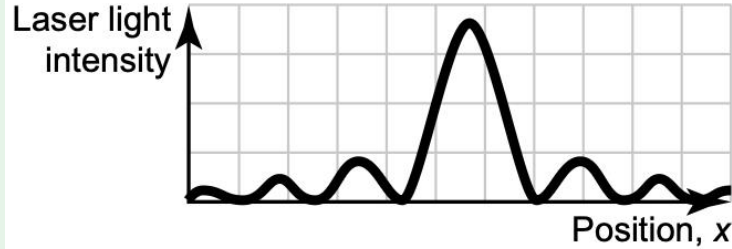


Verify the pattern below by viewing using diffraction glasses and a red laser

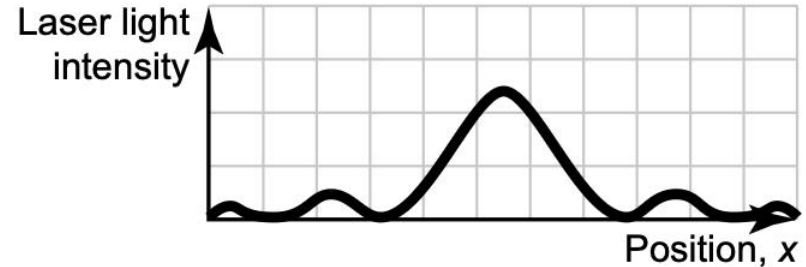


Use diffraction glasses to view pattern using lasers and graph the intensity

Green laser light pattern



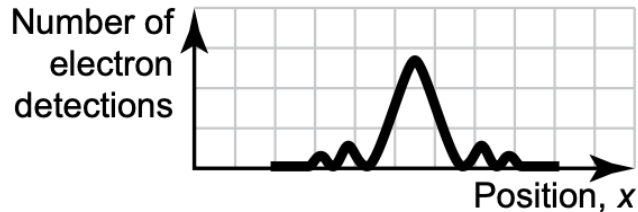
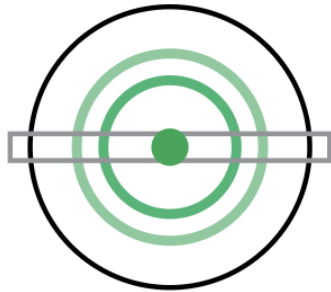
Red laser light pattern



Predict pattern when voltage is increased.
Compare to patterns with diffraction grating and lasers.

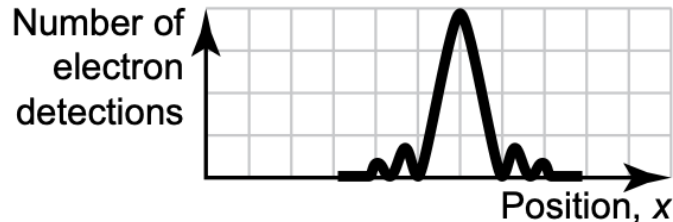
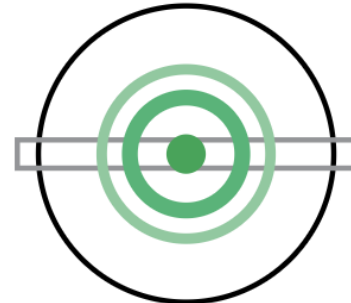
Lower accelerating voltage

Face-on view of screen



Higher accelerating voltage

Face-on view of screen



Comparison of patterns

The lower accelerating voltage is similar to longer-wavelength (red) laser.

The higher accelerating voltage is similar to shorter-wavelength (green) laser.

The wavelength is inversely related to the momentum. This means that when the accelerating voltage is high, the electron behavior is similar to light with a short wavelength (high energy).

Side Note

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

In **1925**, Clinton Davisson and Lester Germer stumbled on evidence for electron diffraction by accident. They were trying to study the structure of atoms by firing low-speed electrons at nickel. In one experiment, their equipment malfunctioned, and they observed strange peaks in their data. It was only later that Davisson learned of the work of Louis de Broglie and made the connection that they had observed the wave-like properties of electrons. Davisson and Germer went back to the lab to test their idea and succeeded in repeating their observations.

The de Broglie relation, describes WP duality by associating a wavelength, λ , with the particle-like property of momentum, p . However it does not explain how they behave over time or how they interact with each other.

Wave Functions

- Properties of a system
- Determined by constraints (i.e. violin)
- Electrons constrained by attraction to nucleus
- Measurements causes wave function to collapse, resulting in particle with definite properties
- Exact location of particle cannot be predicted before the measurement, but probability of location can be calculated (square of the amplitude of wave function)

Can we do better than Bohr?

How should we model electrons? (Note: this is an electron diffraction tube where electrons are ejected and accelerated by potential difference)

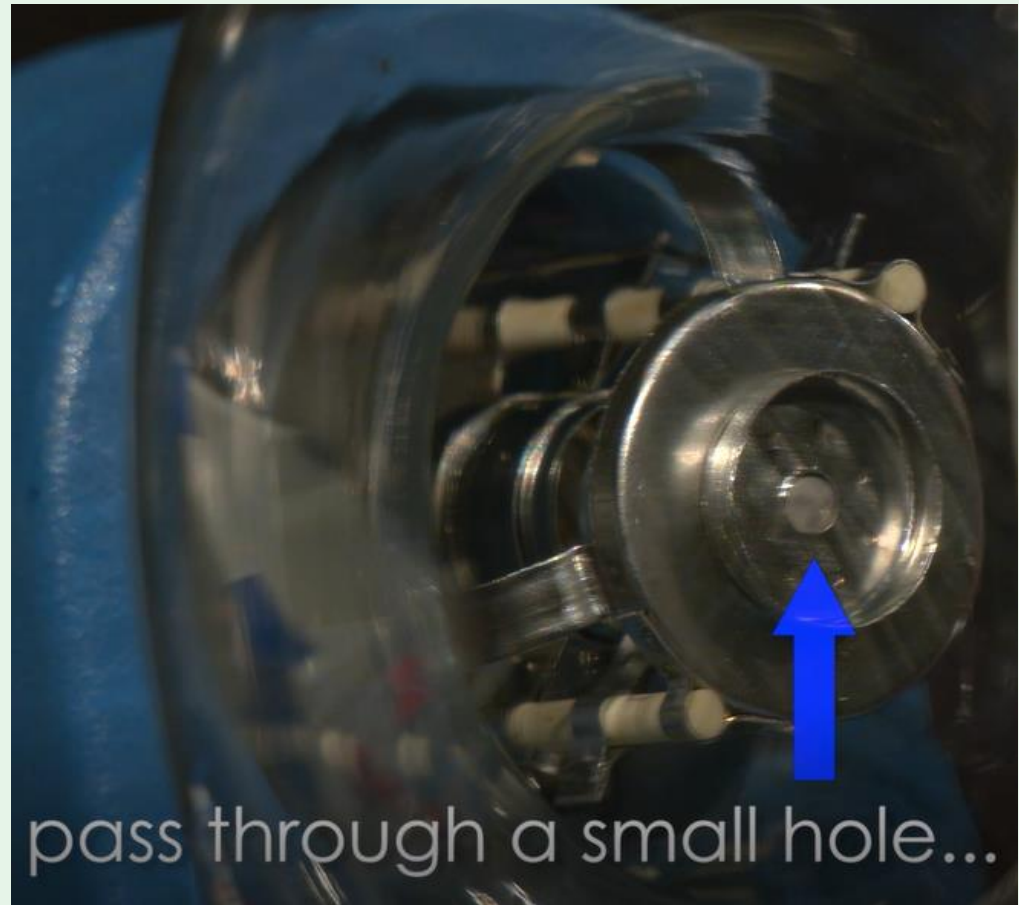


TEACHER NOTE:

The graphite crystal acts like a diffraction grating. Electrons are emitted, accelerated, and pass through the graphite crystal.

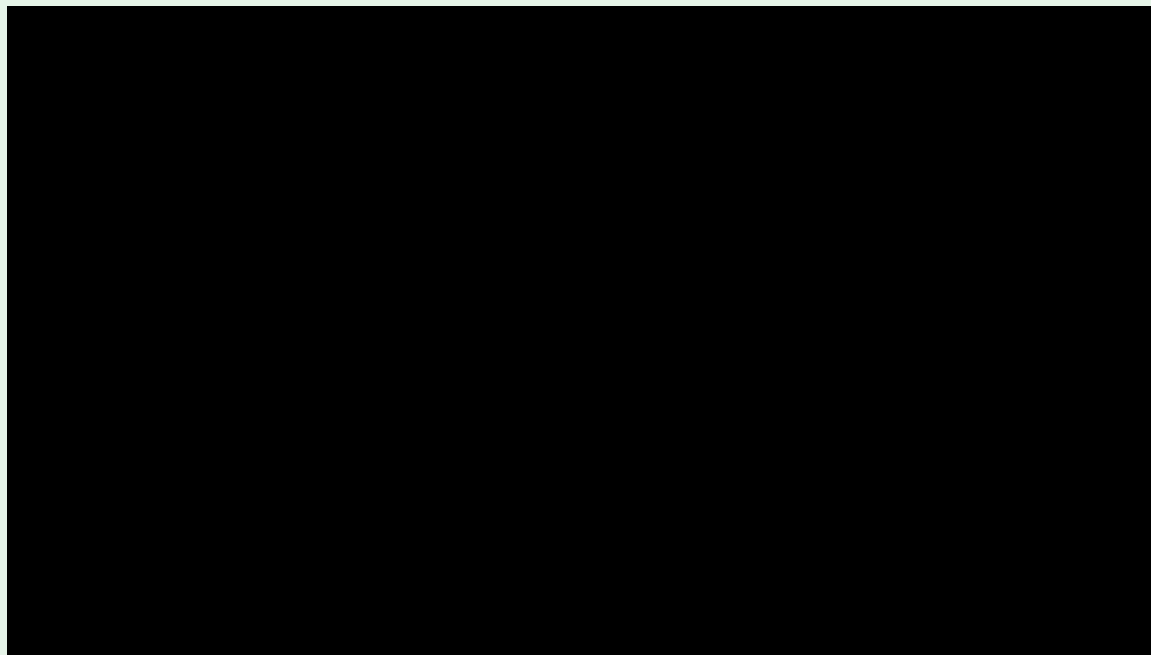
This is similar to the diffraction glasses seen in the engage.

Only allows a few
electrons at a time



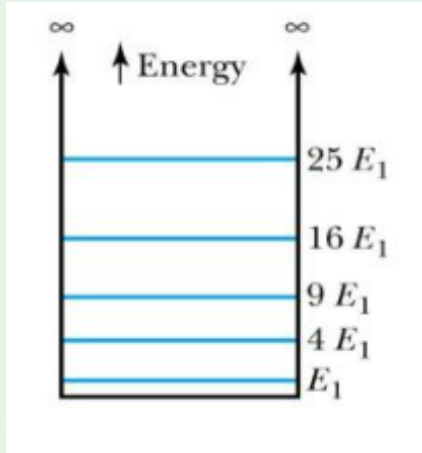
pass through a small hole...

Video



Observation

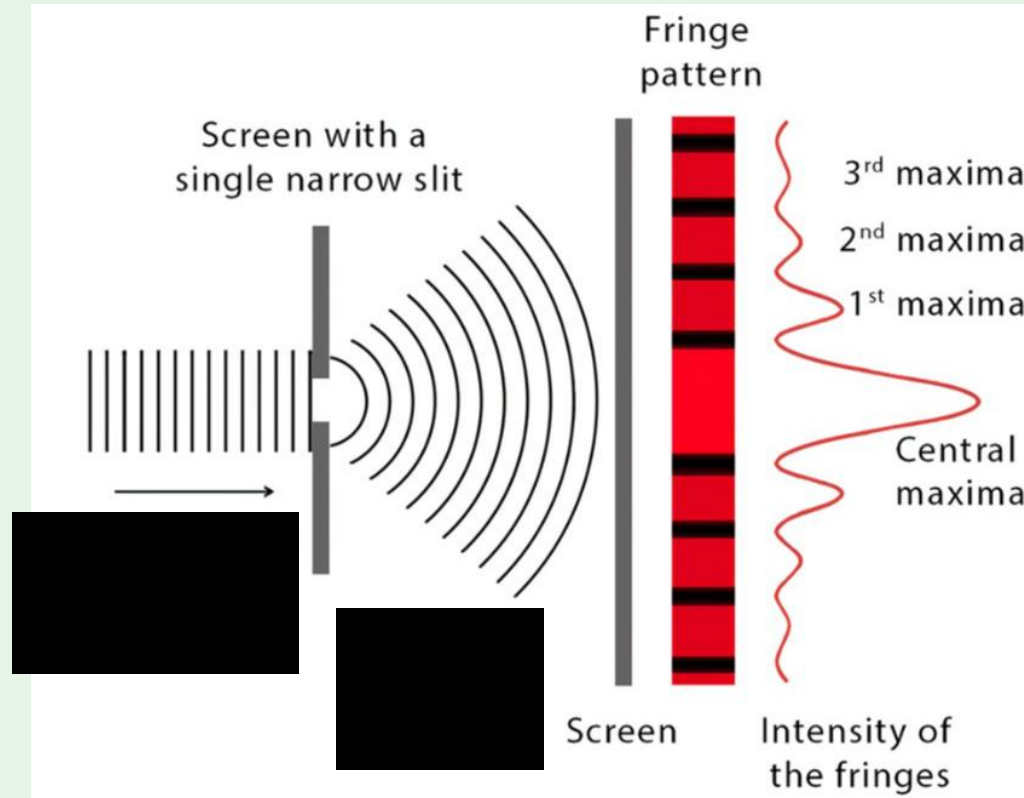
- Probability of electron location follows the quantum number squared



E_1 = lowest energy ($n=1$) NOT zero



Explanation of Observation: Wave Diffraction

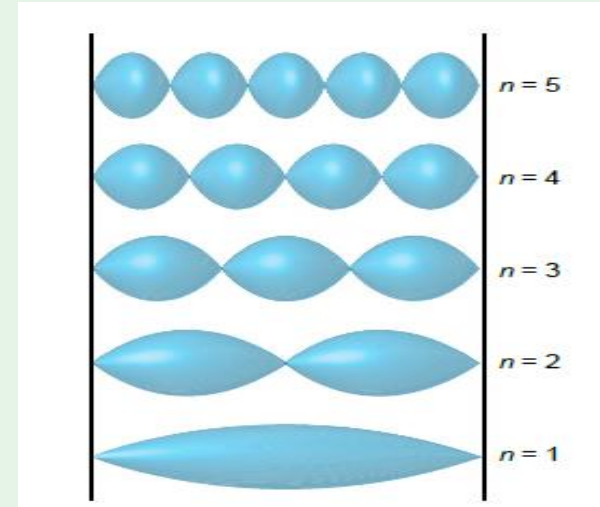
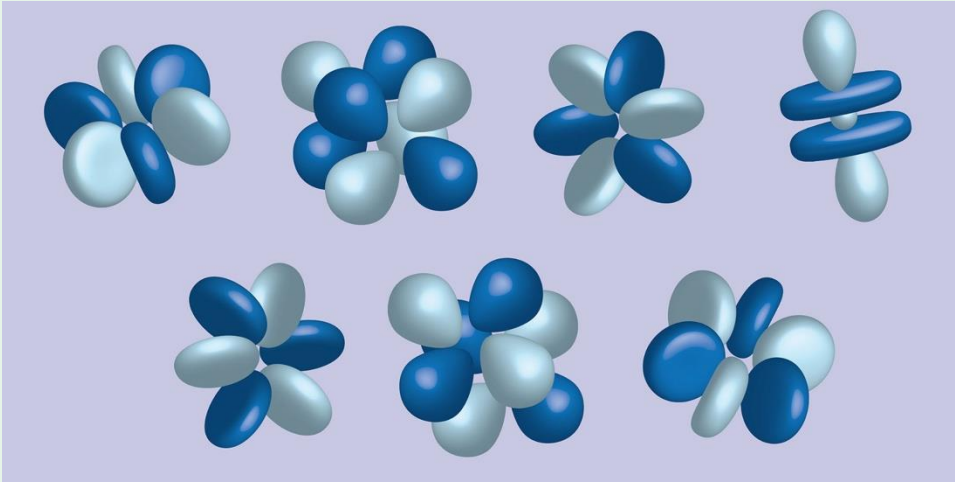


What predictions does modeling electrons as waves lead to?

An electron is a quantum object that is neither a traditional wave nor a traditional particle but is a quantized fluctuating probability wavefunction.



Wave model provides a natural explanation for discrete energy levels and orbitals



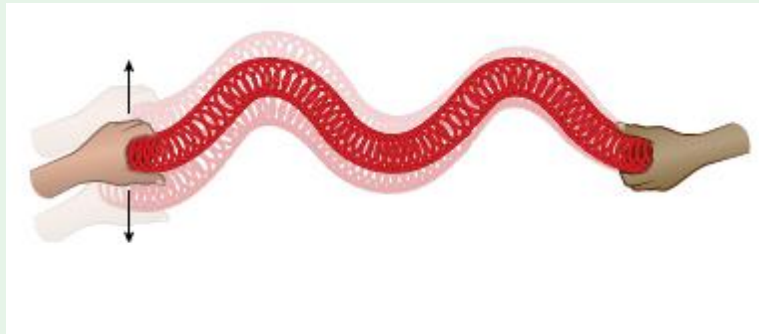
Classical Standing Wave Model

Generating Classical Waves

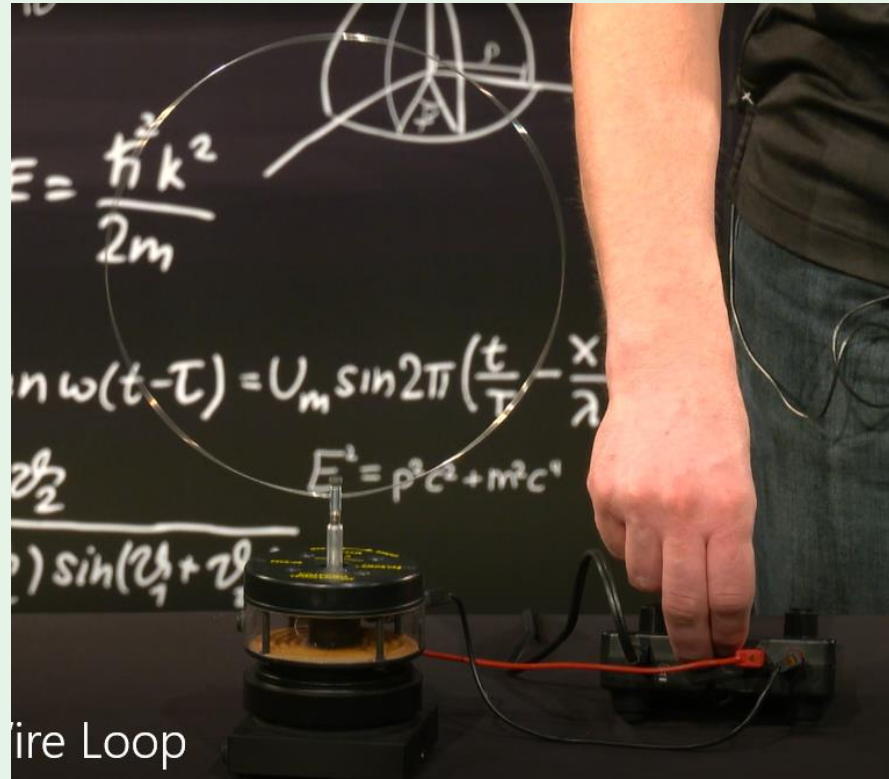
Produce a periodic of standing wave by shaking the spring horizontally on the floor or tabletop. (See Part 1 of PI *Beyond Bohr*)

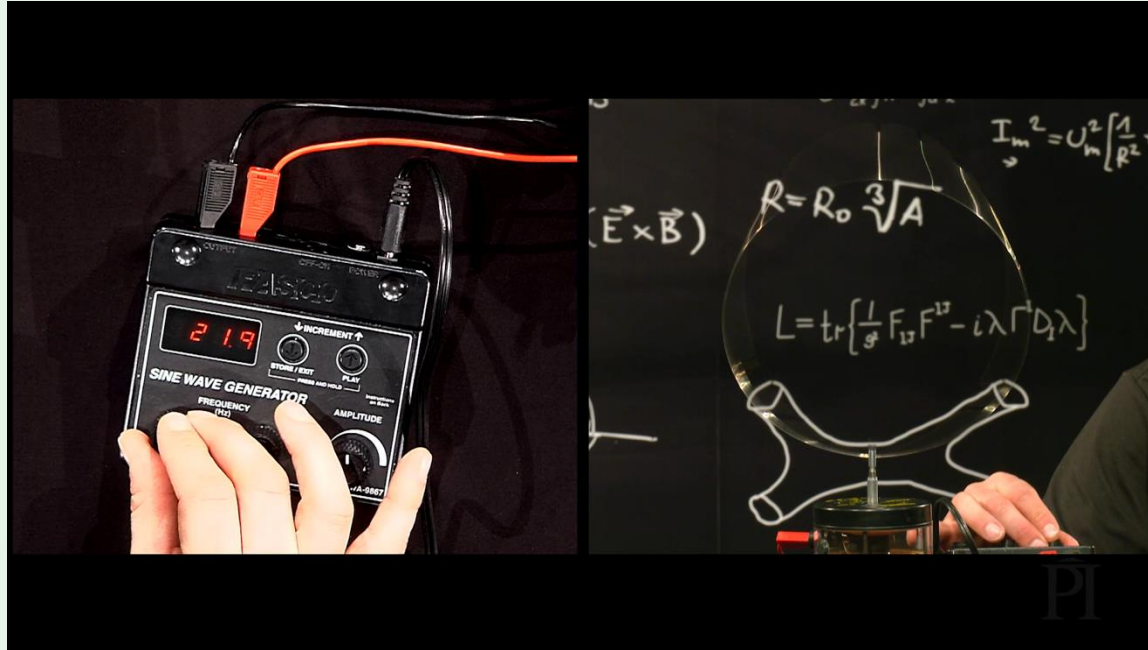
Identify the nodes and antinodes.

Explain what is happening in terms of superposition.

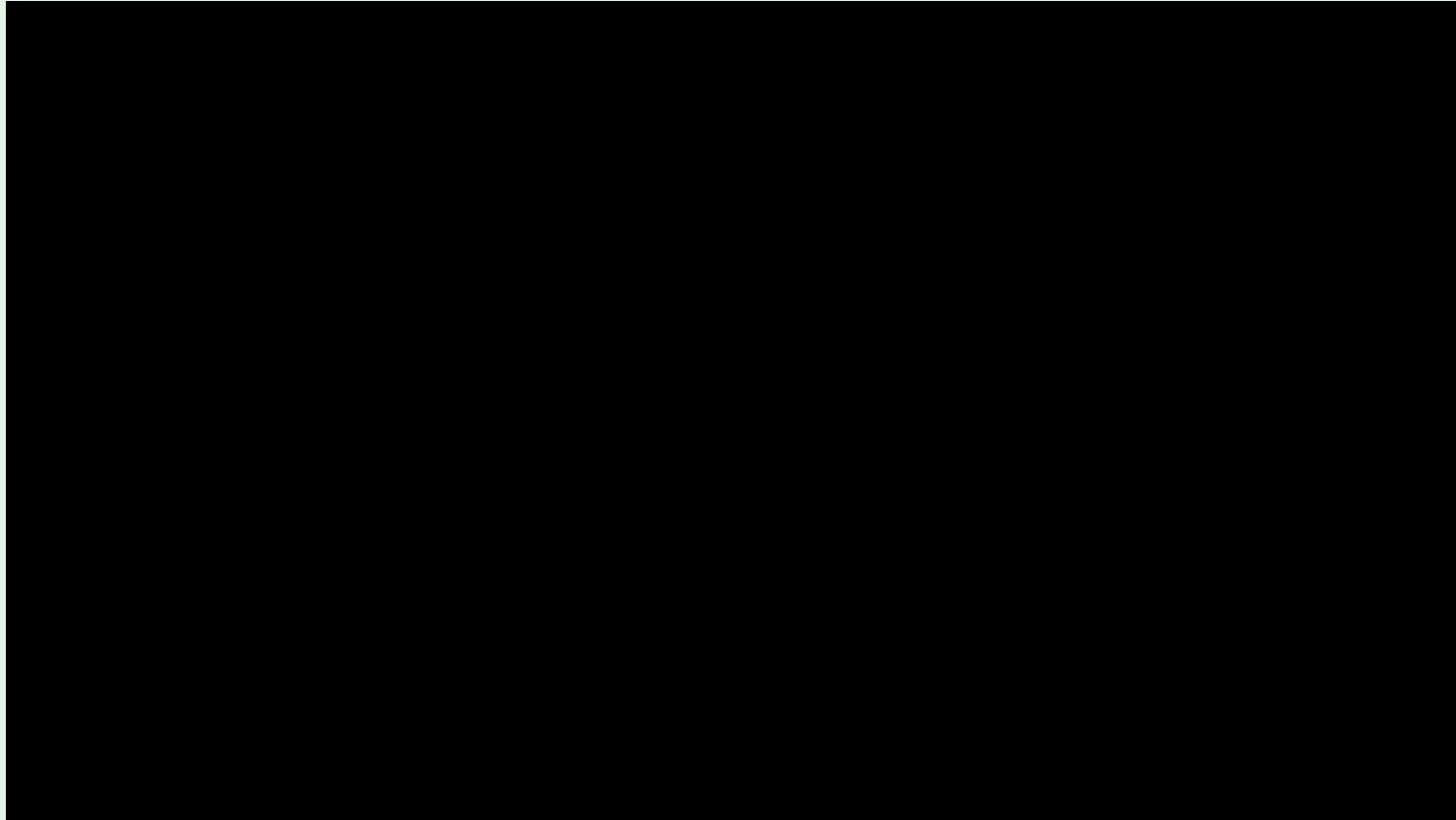


Standing Wave Video: Oscillating Wire Loop

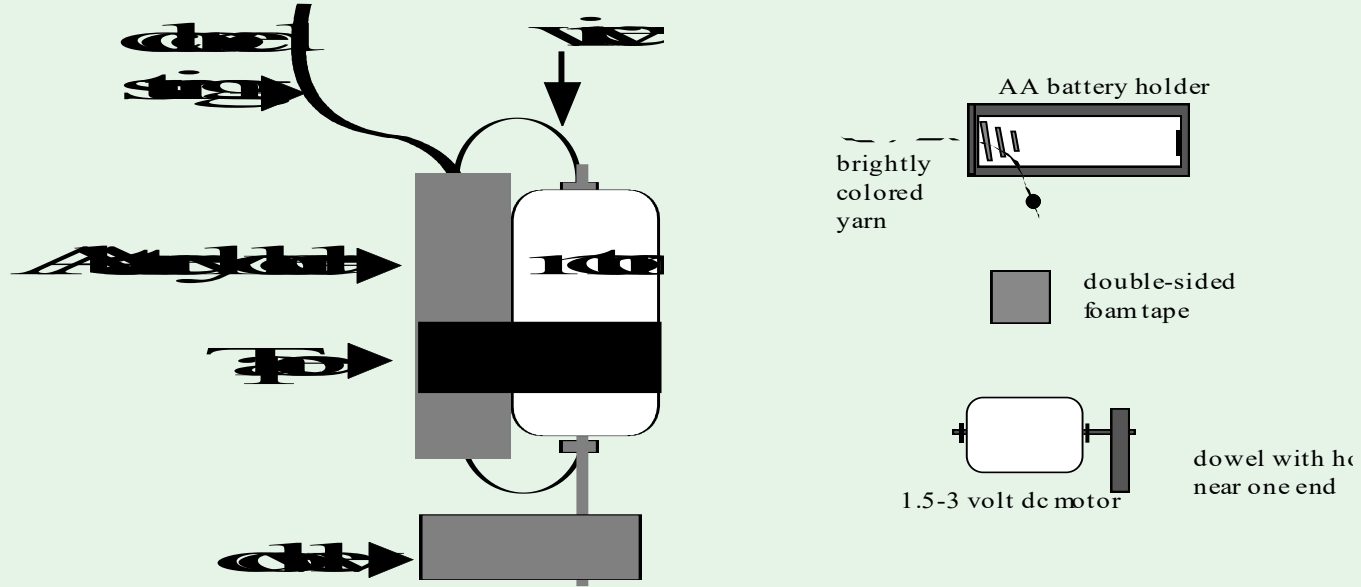




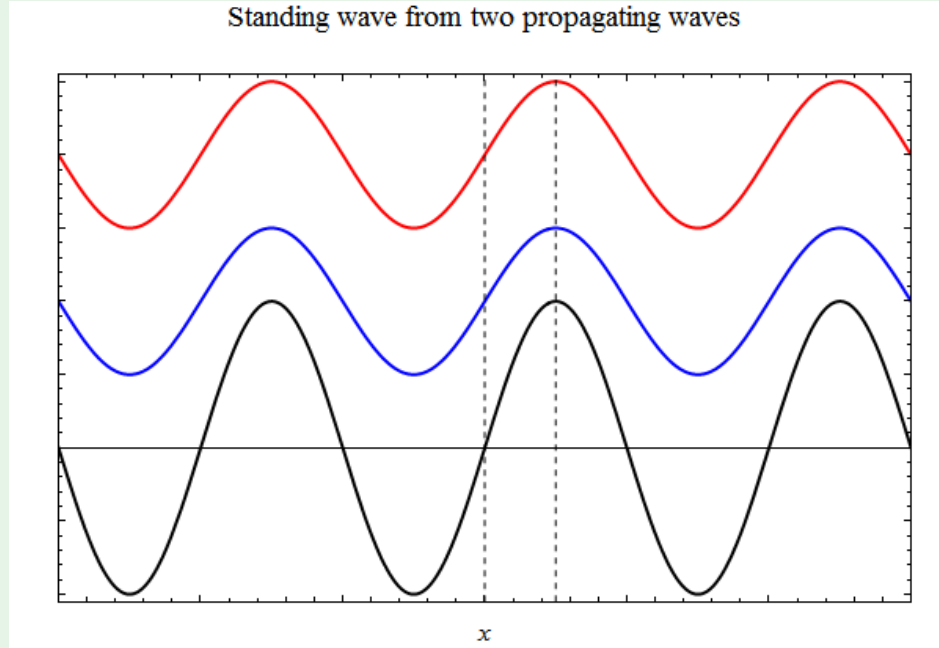
Standing Waves: Ring and Snaky



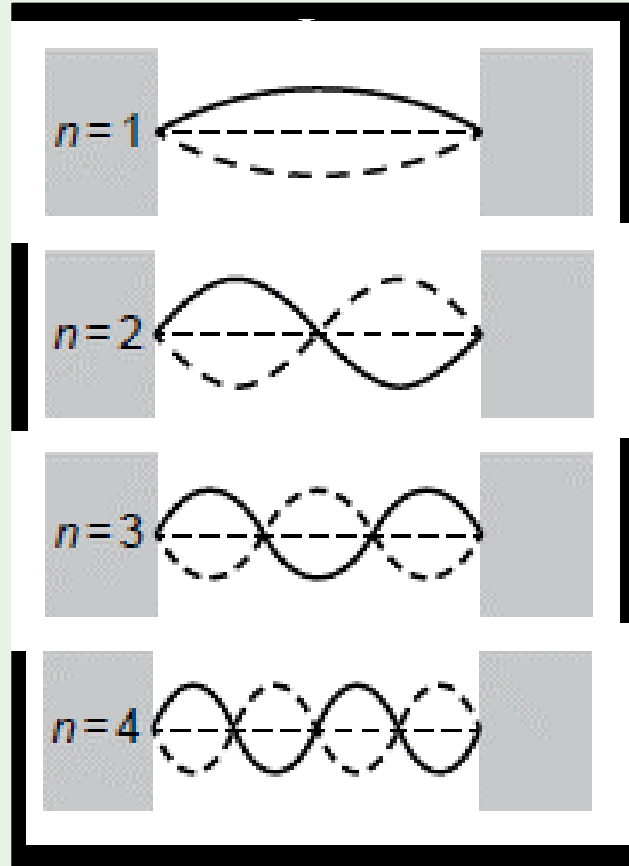
DEMO standing wave generator



Consider Propagating Waves in a Box



Stable configurations of Waves in a Box



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

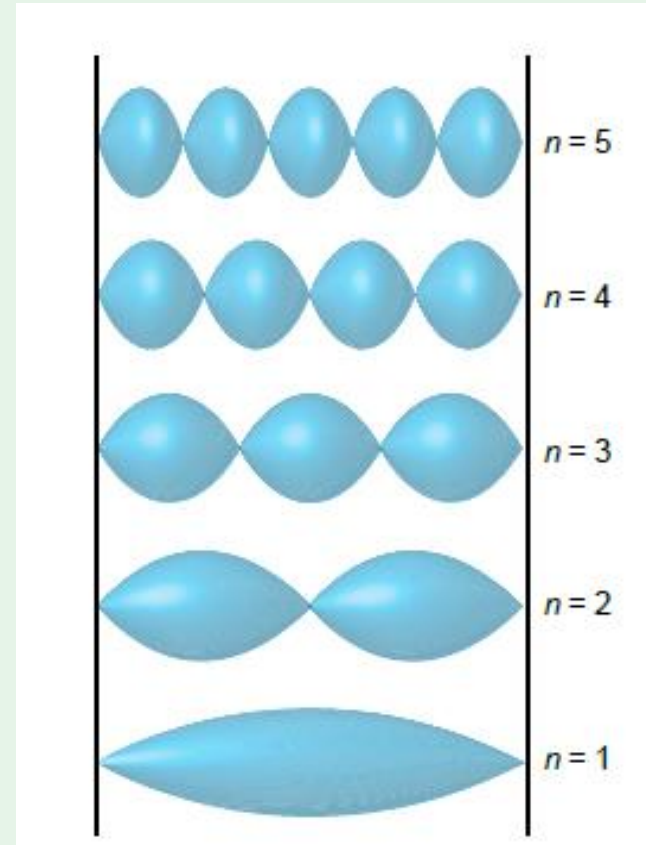
$$L = \lambda$$

$$L = \frac{3\lambda}{2}$$

$$L = 2\lambda$$

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

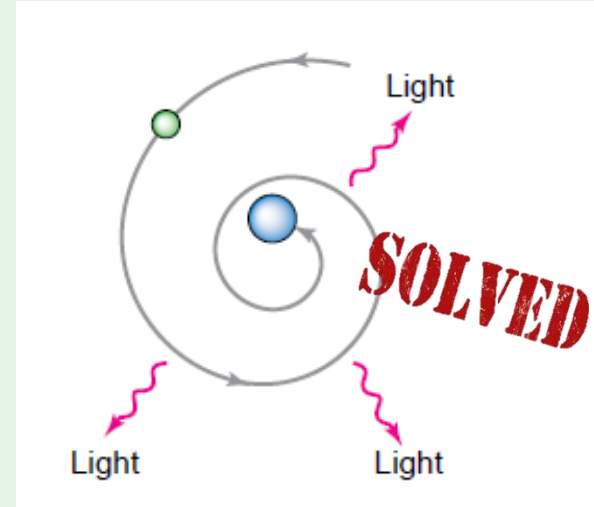
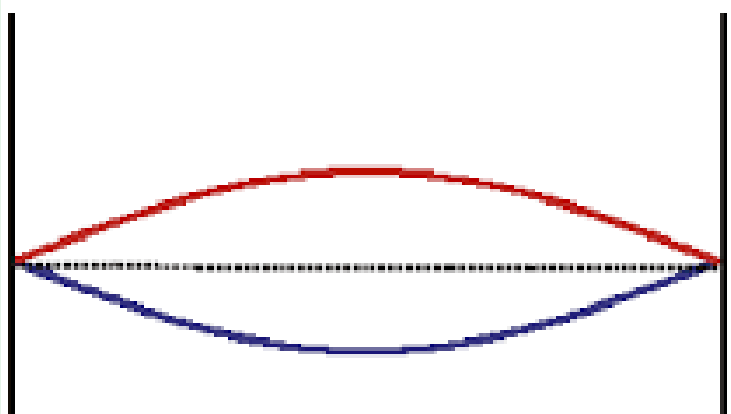
TEACHER NOTE: Anti-nodes are regions of high probability of detecting an electron as a particle.



Zero Point Energy

The lowest energy is half a wavelength.

An electron with zero energy cannot exist.



Back to Bohr

Bohr's model of the atom was a combination of Rutherford's planetary model with Planck's quanta, fixed packets of energy called photons. The restriction to precisely defined orbits was a major problem for the Bohr model of the atom.

de Broglie expanded the idea that particles such as electrons could possess wavelike characteristics.

This prompted Schrodinger to suggest the idea that electrons were matter waves. Matter waves became the foundation for the Quantum Mechanical or Electron Cloud model of the atom.

The atomic nucleus is surrounded by probability “clouds” of electrons called orbitals, which is a better representation of the actual quantum physics of atomic structure.

Activity (Perimeter Institute HO see Part 2)

Use a check mark (✓) to indicate each location where the probability of detecting an electron is the highest. Use an X to mark each location where the probability of detecting an electron is the lowest (i.e. nodes)

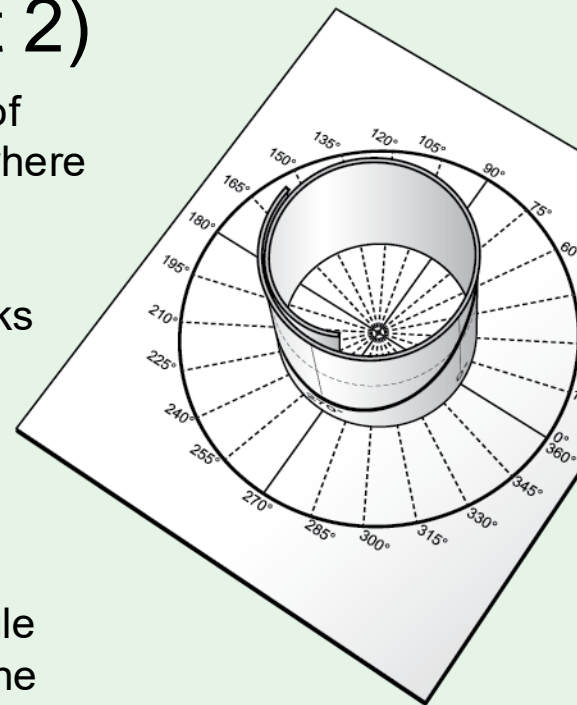
Bend the template so that it forms a cylinder and the 0° and 360° marks meet. Secure ends. How many wavelengths fit around the circle?

Center the cylinder on the circular Graph and make sure the 0° on the template matches with the 0° on the circular graph.

On Circular Graph A, draw an X on the edge of the circle at every angle where there's an X on Wave Template A. Repeat this process for all the check marks (✓) on Wave Template A.

On Circular Graph, shade the segment to the left and the right of each checkmark. What do the colored regions represent?

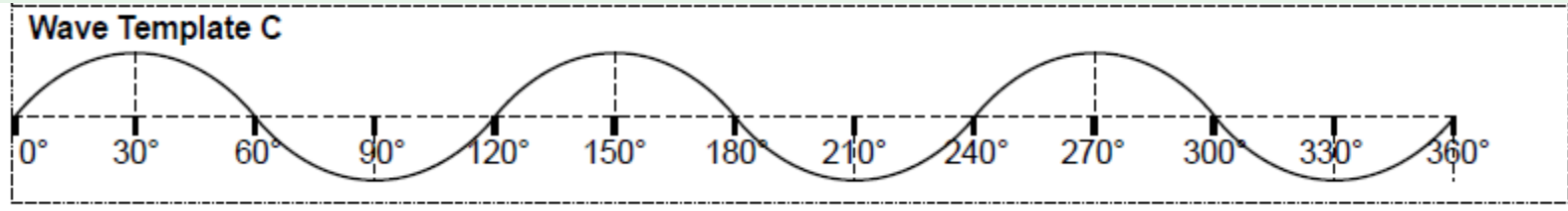
Compare graphs A, B, and C.



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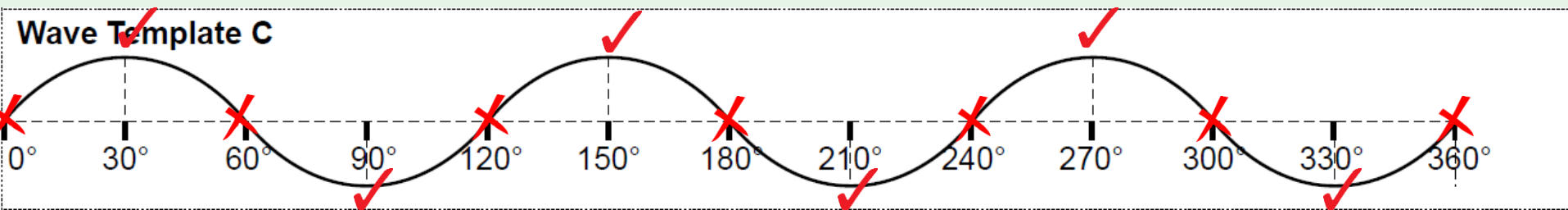
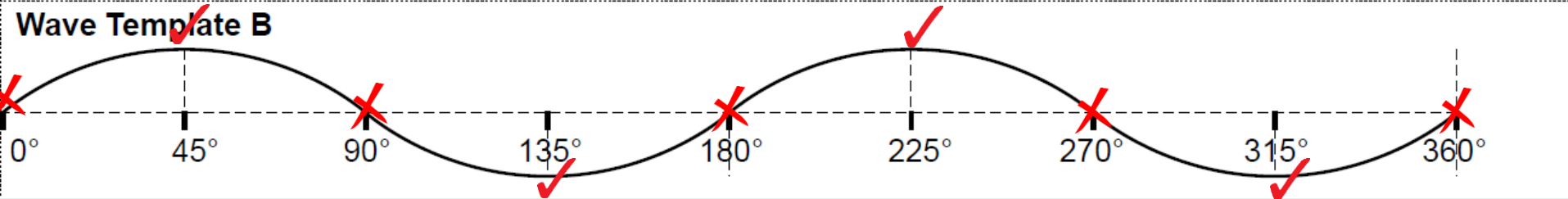
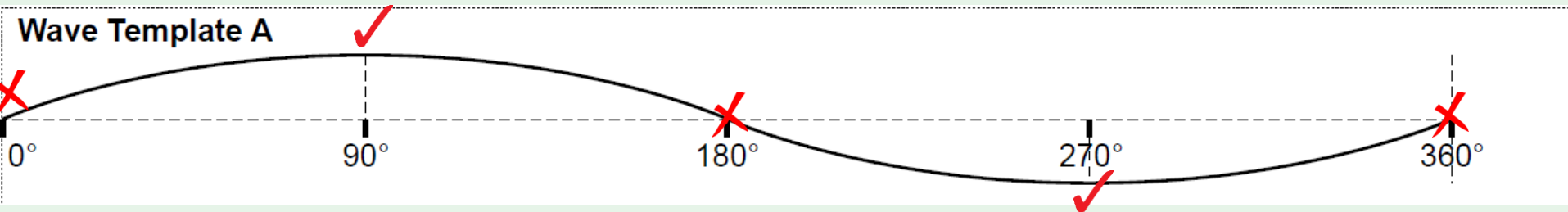
Wave Template



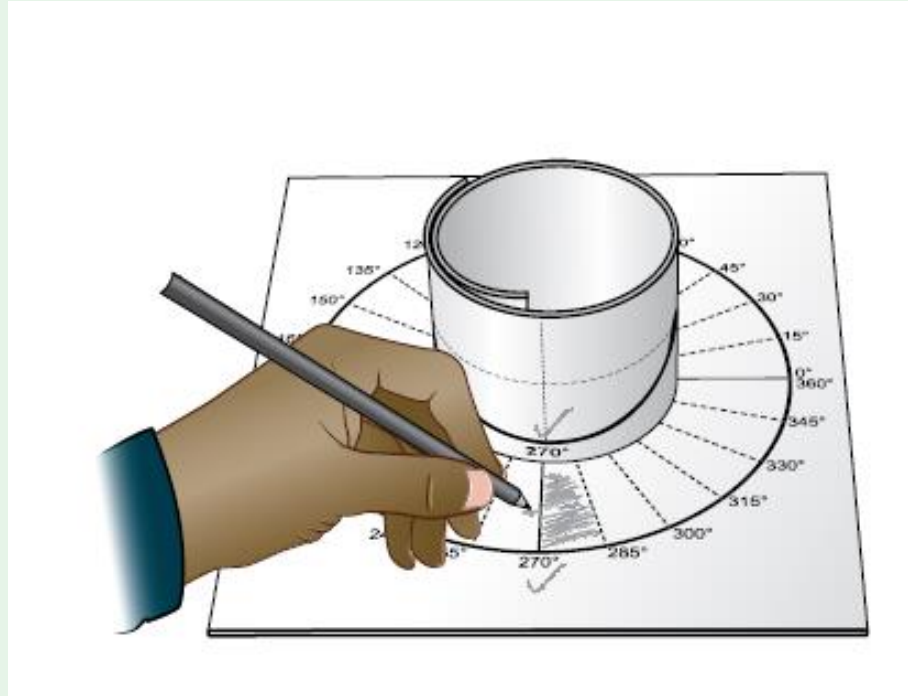
Mark locations where the probability of detecting an electron is highest



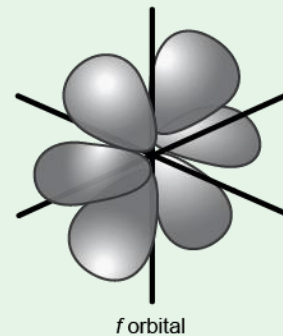
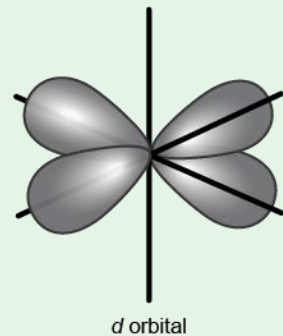
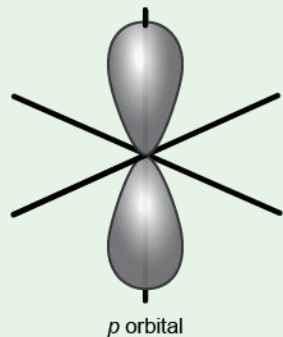
Mark locations where the probability of detecting an electron is lowest



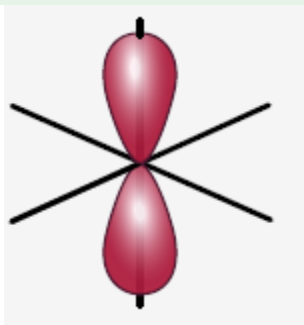
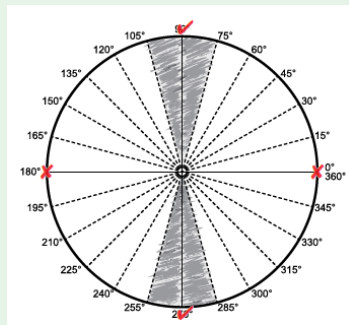
Shade in the Zones



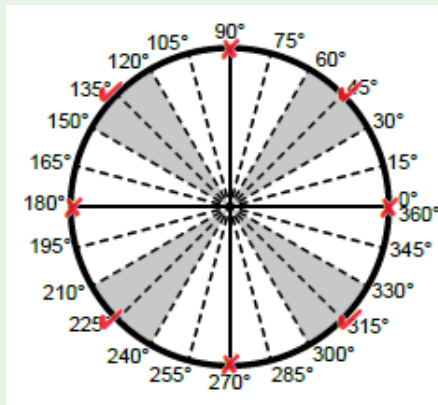
Continued....



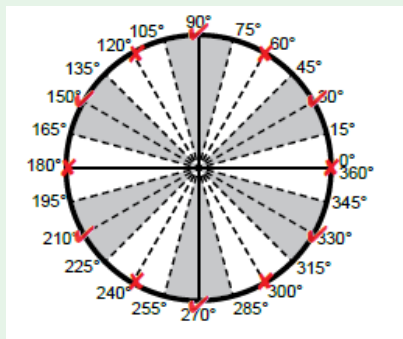
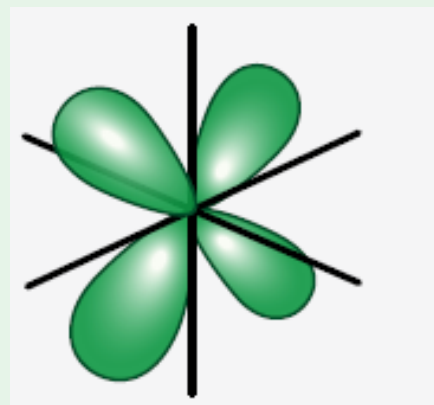
- Compare the patterns you made on the circular graphs to the images of the p , d , and f orbitals below. Keep in mind that we are modelling 3-D orbitals with 2-D graphs. Which pattern best matches each orbital?
- Shade Circular Graph D to represent an orbital where there's an equal probability of detecting the electron at every angle. What type of orbital does it correspond to?
- In your own words, summarize why orbitals have these shapes.



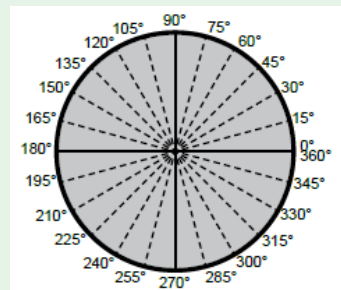
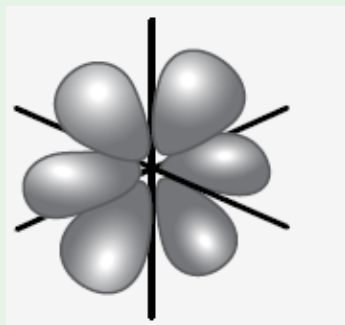
p orbital



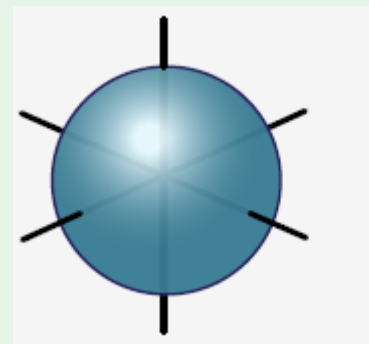
d orbital



f orbital



s orbital

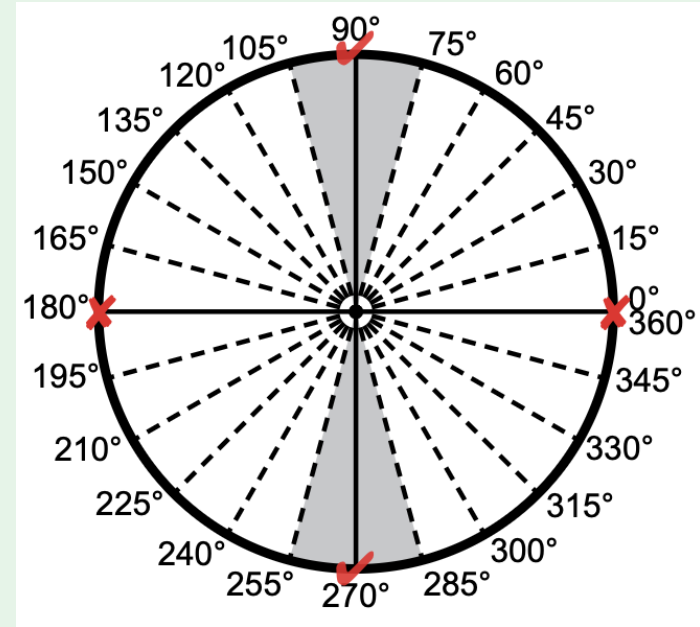


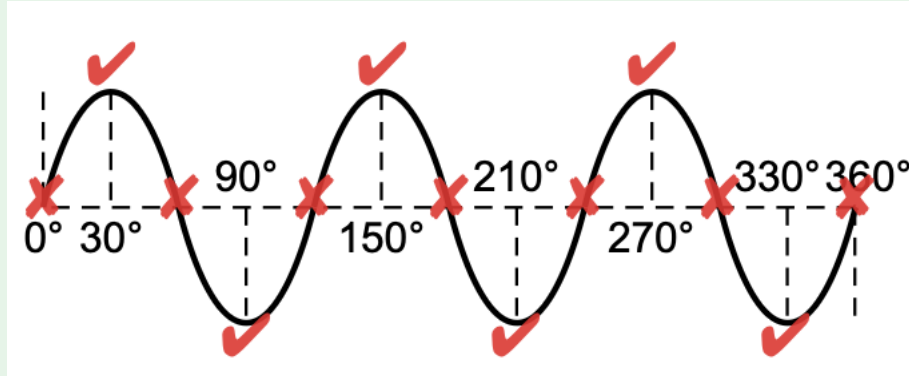
Connection to wavelengths

Where is the standing wave?

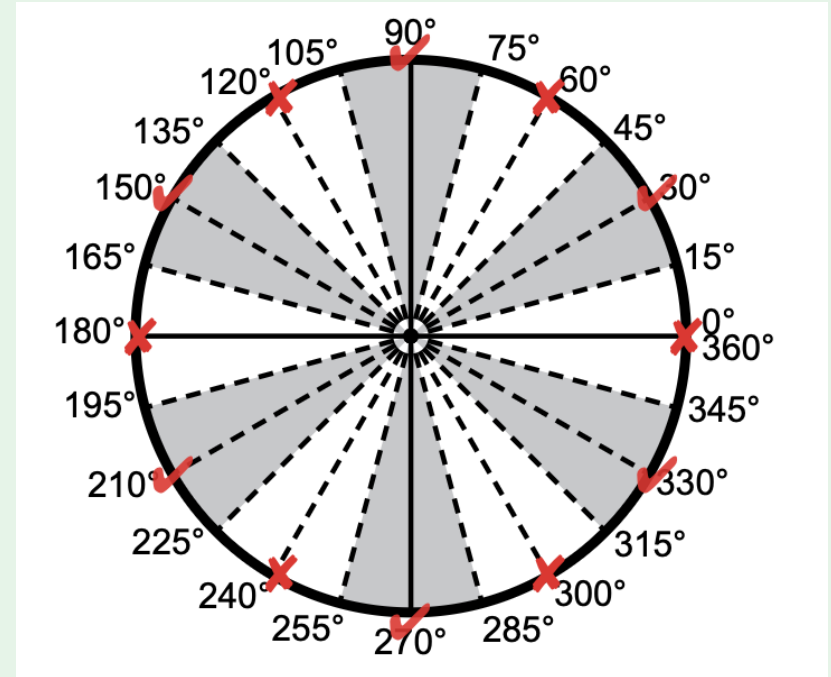
How many wavelengths are present?

ANS: One wavelength



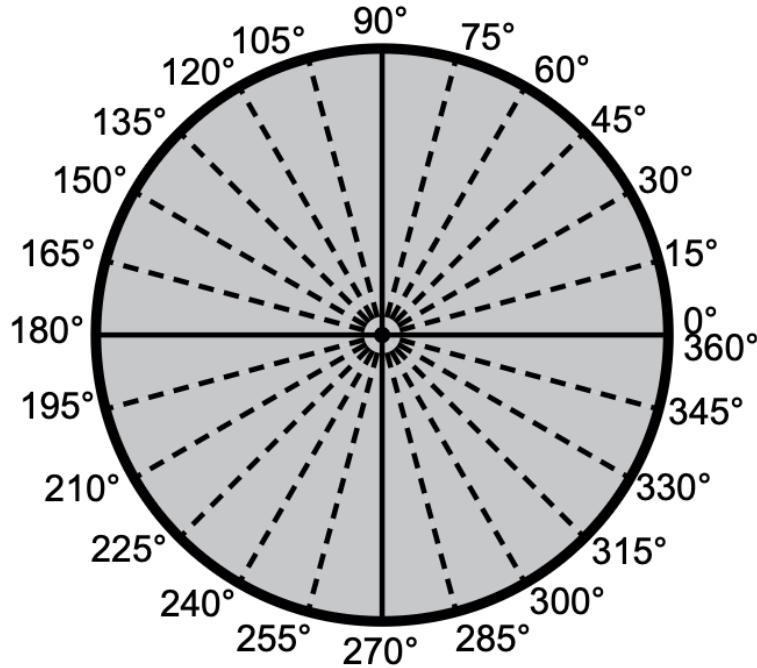


ANS: Three wavelengths



Which orbital is represented?

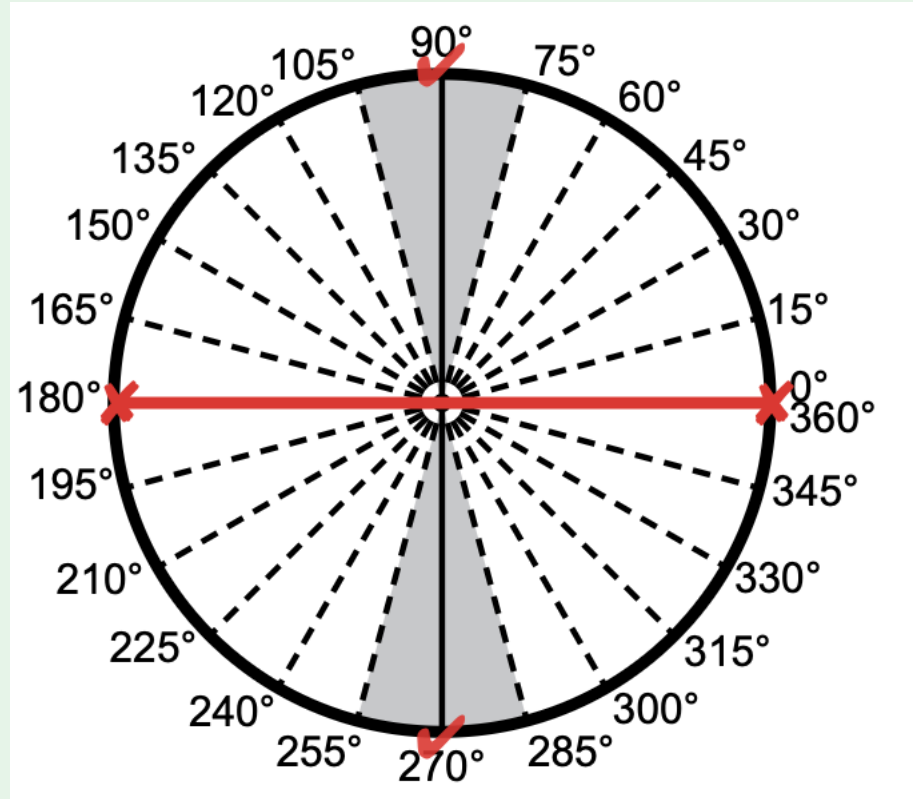
ANS: S



Circular Graph Label	Orbital	Number of Nodal Lines	Orbital Quantum Number, ℓ
D	s	0	0
A	p	1	1
B	d	2	2
C	f	3	3

If a line is drawn from X to X,
what does it represent?

ANS: Nodal lines or



Connection to Spectral Lines (from PI)

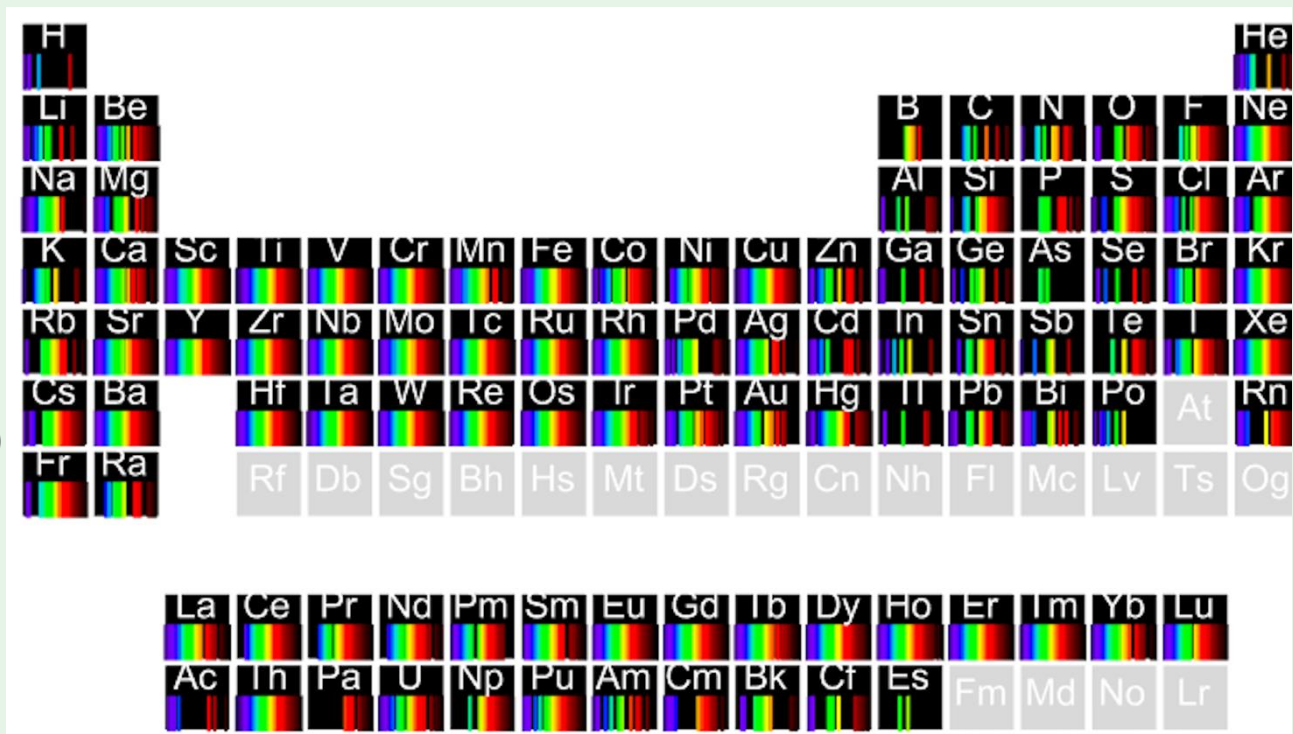
Analyzed spectra of various elements (19th century) and grouped the spectral lines observed into 4 categories.

s = sharp (narrow and sharp)

p = principal

d = diffuse

f = fundamental



Quantum Dots

Can we constrain wavelengths in a confined space?

Superposition of Waves

Types of Interference

Quantum Superposition

Collapse when measured
Double slit (interference
pattern)

Veritasium video:

<https://youtu.be/luv6hY6zsd0?si=rVE4FfEjreD5Ad5X>

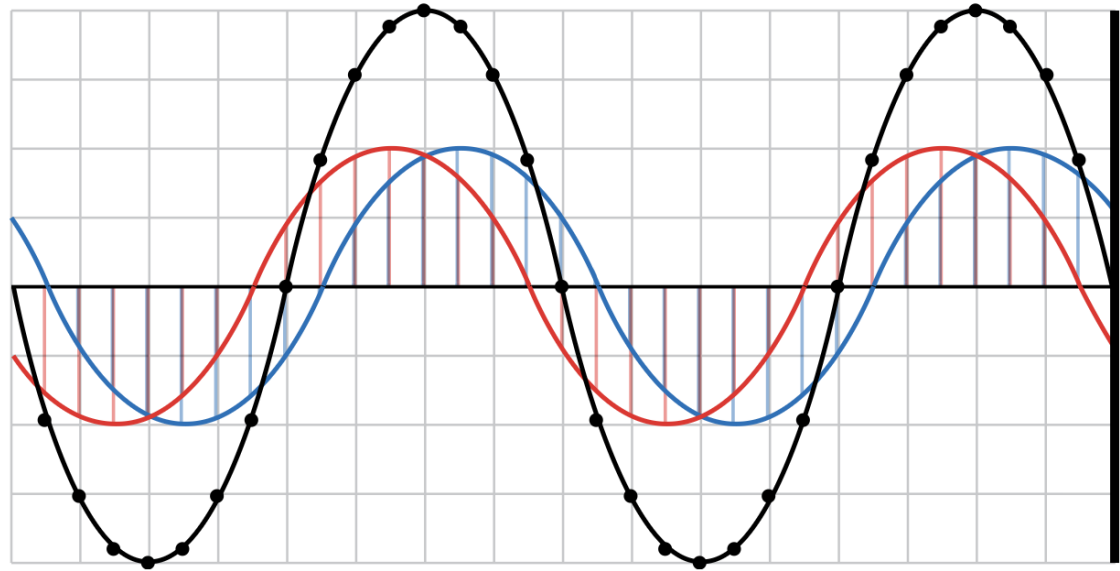
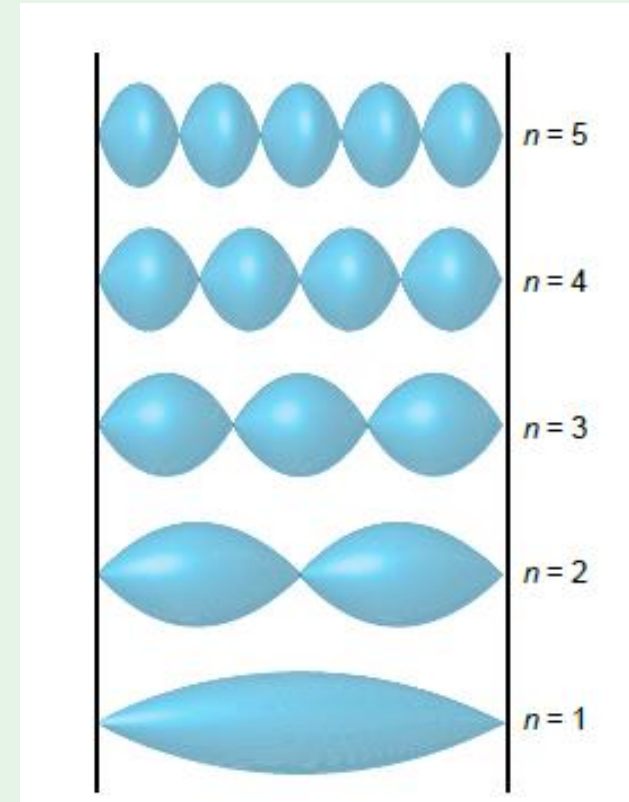


Figure 5 The right-travelling wave (red) reflects off the wall of the box (far right), generating a left-travelling wave (blue). The two waves add together in superposition, generating the black wave.

- Traveling waves can spread throughout the box resulting in **superposition**.
- A stable configuration can form if the length of the box is whole-number multiple of $\frac{1}{2}$ wavelength (called standing wave)
- n =number of half-wavelengths or antinodes; must be positive integer; only discrete sets of energies are possible with the lowest being 1 and 2.
- Snaky and standing wave DEMO



Electrons and Quantum Dots

A quantum dot is a very small nanocrystal semiconductor made of roughly a million atoms and electrons. The electrons are tightly bound to the nuclei, with a few number of free electrons in the dot.

Nobel Prize in Chemistry 2023

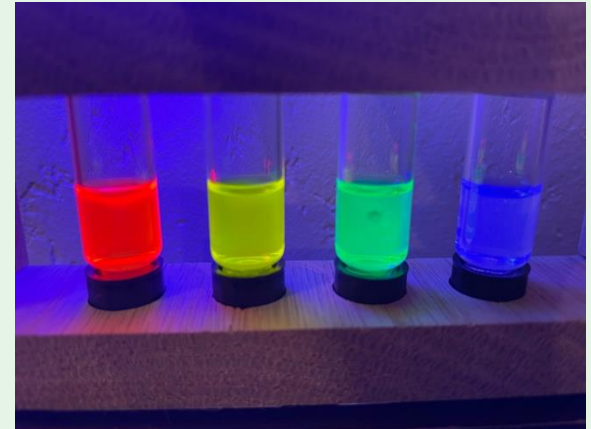
<https://youtu.be/AF8d72mA41M?si=nsZfUdNWYbPOE3wv>

Making Quantum Light

Quantum for All channel

<https://youtu.be/N8JwozHGEXc>

You tube (Quantum dots in fabrication)
(summary next slide)



Summary of Video

- Optical quantum devices require steady stream of single photons, not random as in regular light.
- Many uses require conversion from classical and quantum light
- Electron is trapped in box and excited with a laser which leaves a hole in the ground state.
- Returning to ground states it recombines with the hole and emits a single photon
- Making the “box” requires semiconductors
- Changing conditions changes the size of the quantum dot which determines color of photon emitted (smaller = higher energy)
- Emitted photons are guided for use in communication or quantum computers

Quantum Connections (LEDs, Quantum Dots)

- Electrons in low energy state (valence band), jump to high state (conduction band). When they fall back the energy emitted as a photon.
- Quantum Wells—trap electrons and holes in the same small space
- Color control—size of energy gap dictates the color. Bigger gap makes high energy blue light, smaller gap is lower energy red
- Quantum Dot LEDs (QLEDs)—tiny crystals (Quantum dots) are paired with a blue LED; size of dot dictates color it glows.

<https://youtube.com/shorts/KnhO3NmHv8w?si=FMunO5IMPitfTjmk>

- QLED dots emit very small wavelengths, giving clarity and brighter display

Standing waves and quantum dots

- Confinement turns freely moving electron waves into discrete **standing waves**, resulting in quantized energy levels and size-dependent optical properties
- When confined to semiconductor (few nanometers) electron waves reflect off the edges and interfere with themselves
- Stable standing waves form when there is an integer number of half-wavelengths so they fit precisely inside the dimensions of the quantum dot.
- Shrinking the dot forces the standing wave to shorter wavelength, increasing the momentum and increasing energy level
- Motion of an electron is described by the motion in space (probability density)
- As it reflects off the walls, it interferes with itself (ex acoustics and wave optics)

Quantum Dot Technology

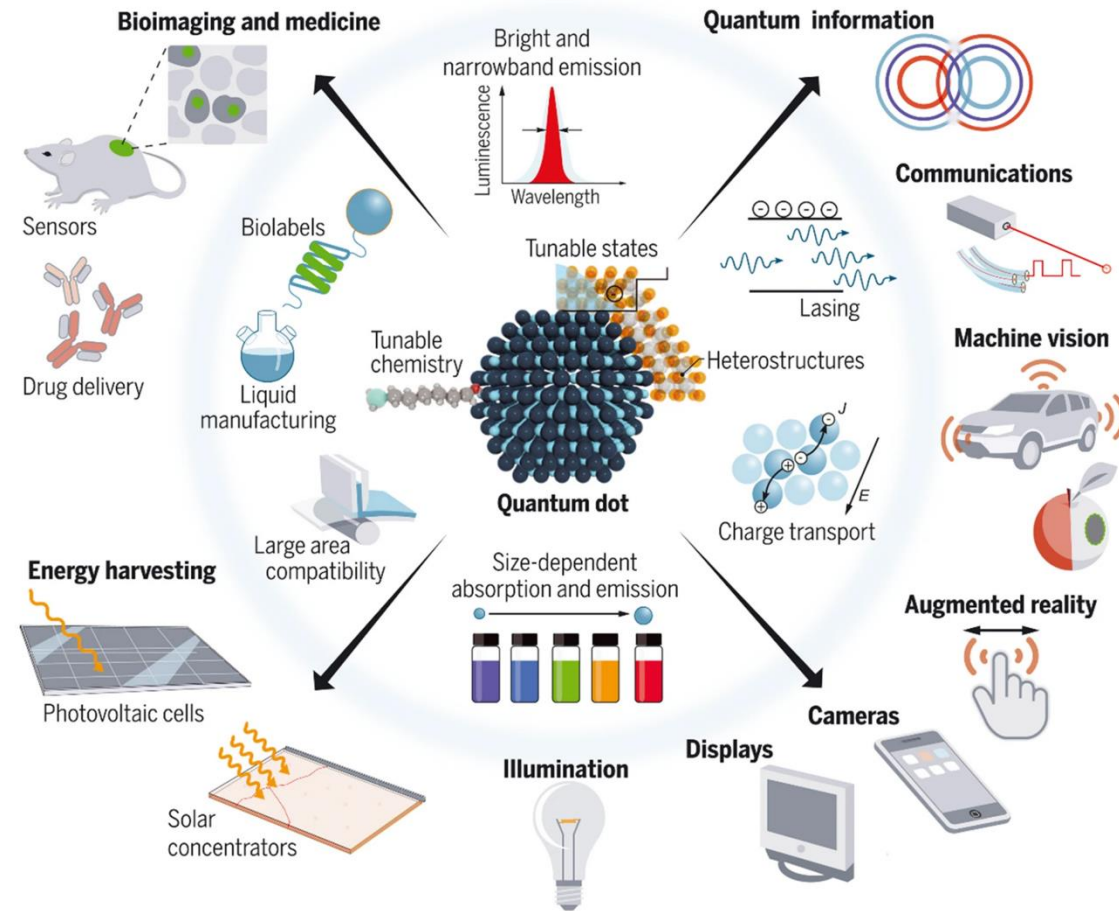
- Semiconductor nanoparticles
- As electrons escape their atomic orbit, they create a conductance region
- Quantum Confinement: Larger dots provide lower energy emissions, smaller dots have higher energy emissions (Standing wave)
- Applications: solar cells, medical imaging, computing, (QLED) TVs, semiconductors
- Addition of red quantum dots to yellow (LED) lights improves spectral content by using an encapsulation process that improves efficacy 20% by reducing amount of red which cannot be seen anyway.

In demo the sizes are the same but the outer shell and inner core change in density, wavelength varies



Quantum Dot Resources

- <https://www.youtube.com/watch?v=fOFrlbW2MmQ>
- <https://spectrum.ieee.org/the-wave-function-and-quantum-dots-nanotechnology-videos>
- <https://youtu.be/fqSUDLTjaCA>
- <https://youtu.be/AF8d72mA41M?si=nsZfUdNWYbPOE3wv>



Application fields of QDs exploiting their unique size tunable optical properties such as energy harvesting, conversion, and storage, optoelectronic devices such as displays, detectors, and laser, communication and information technology, bioimaging, biomedical assays, and sensors. From ref. [45]. Reprinted with permission from the American Association for the Advancement of Science (AAAS)

Dimensionality

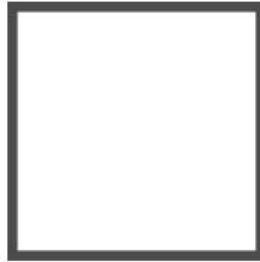
0d (dot)



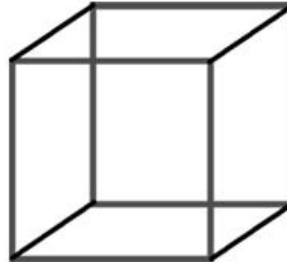
1d (line)



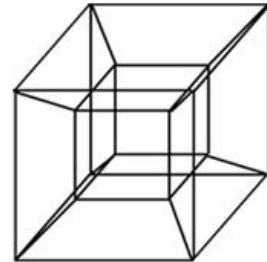
2d (square)



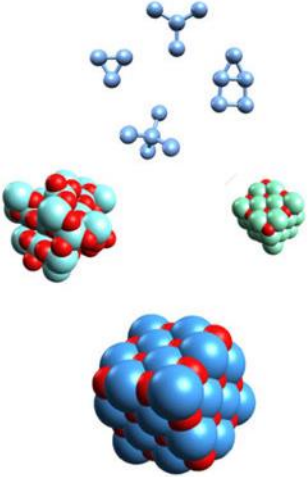
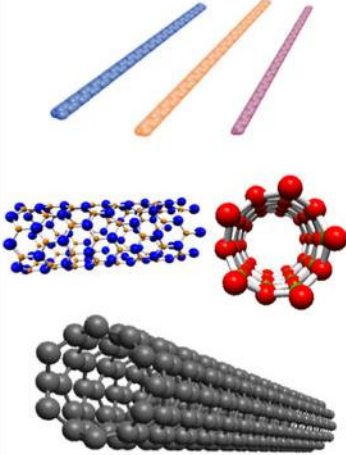
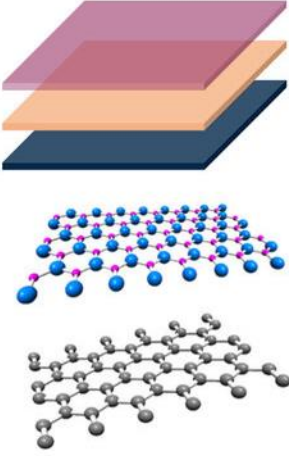
3d (cube)



4d (tesseract)

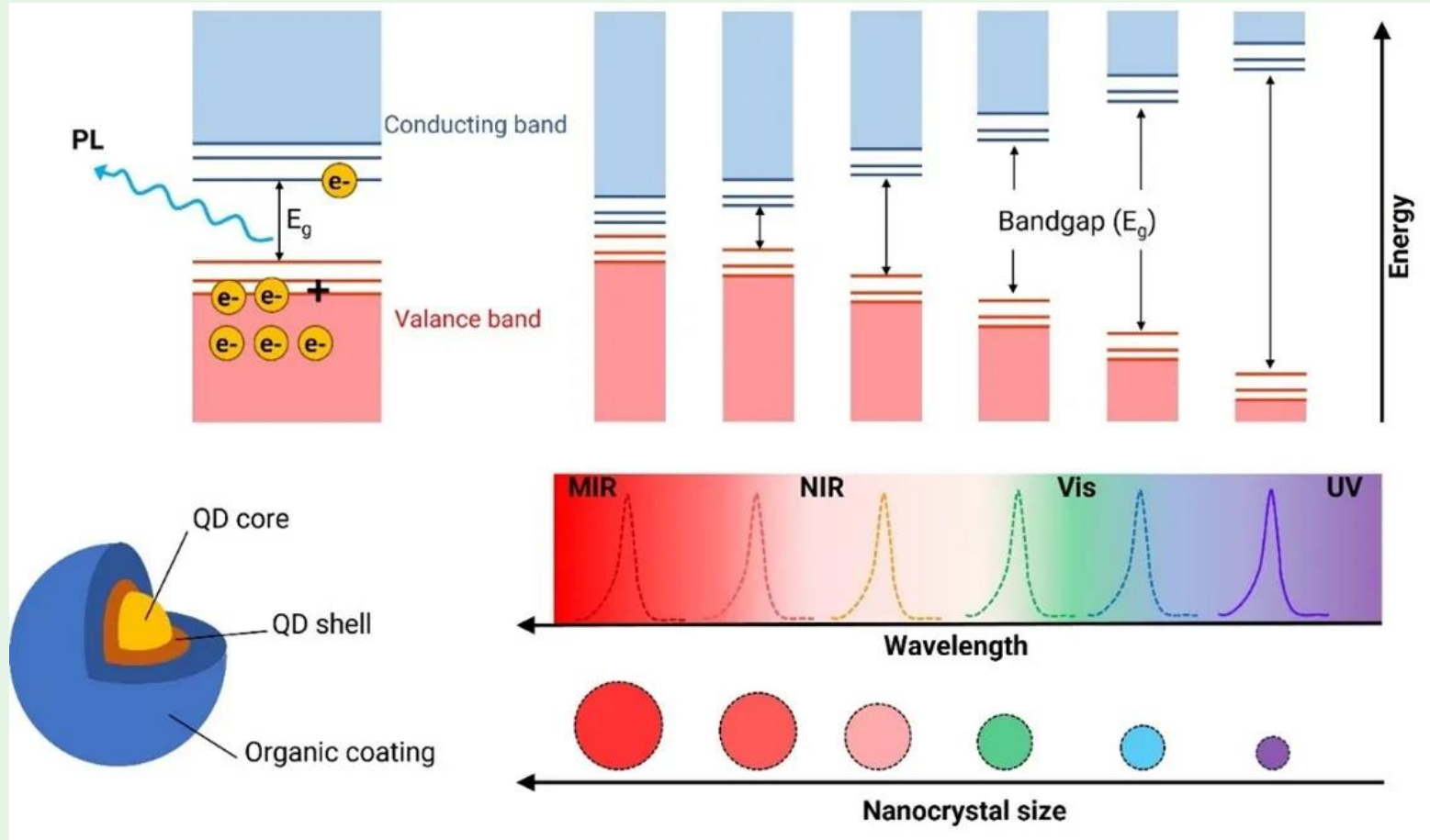


Dimensionality

0D	1D	2D
Diameter <10 nm	Diameter 10-100 nm	Thickness <100 nm
		
Spheres, Cluster, Dots	Wires, Rods, Tubes	Sheets, Platelets, Films

<https://www.nature.com/articles/s41467-021-23278-7>

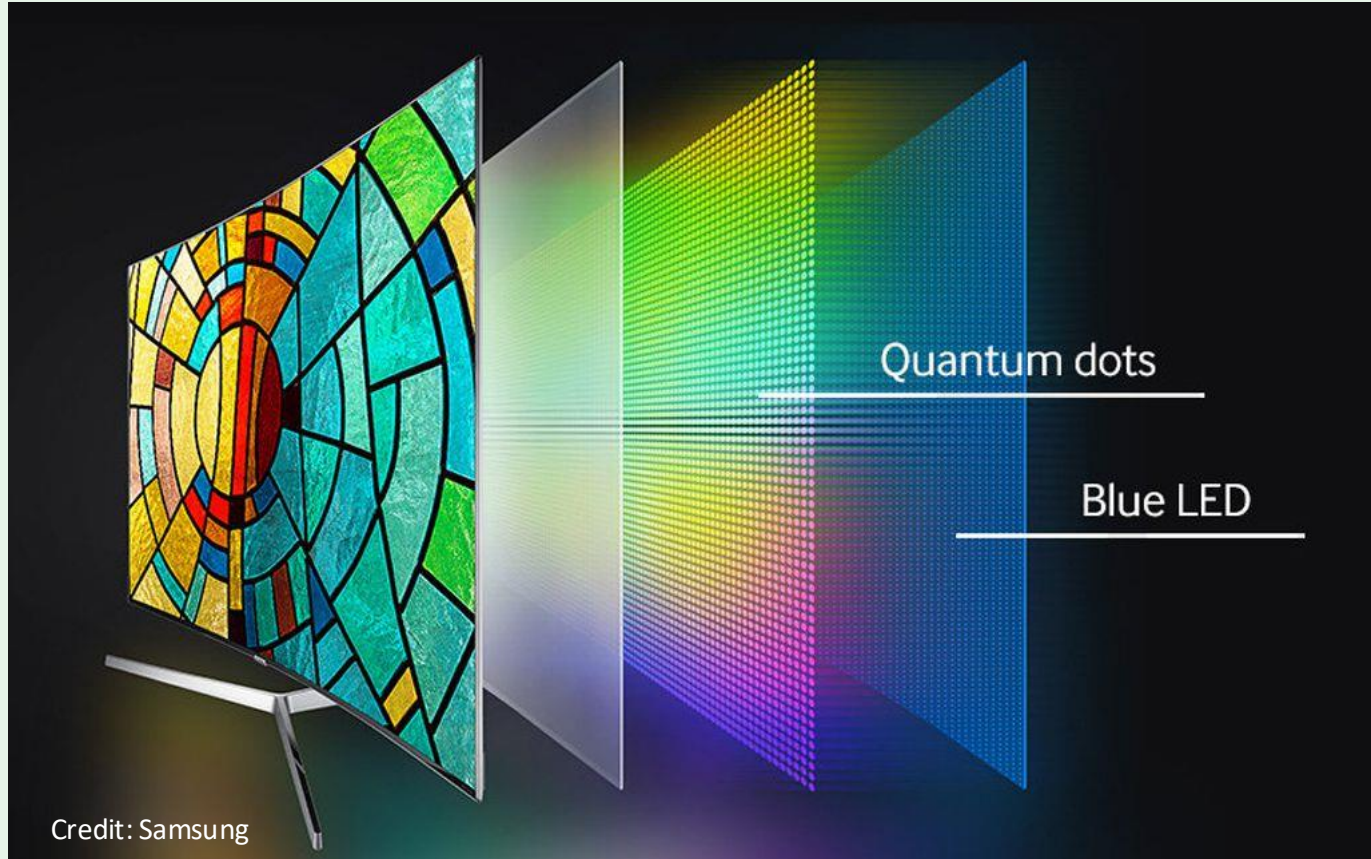
Quantum confinement



Quantum confinement

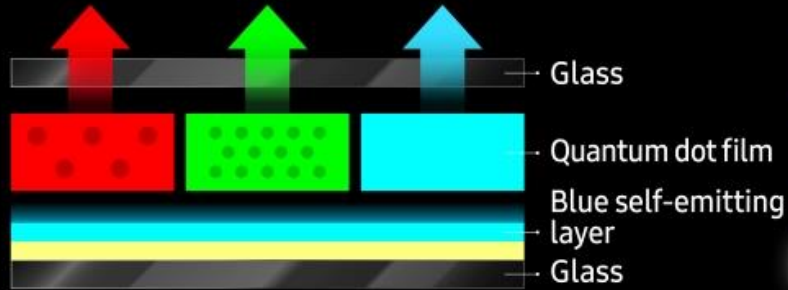


QD Applications: Display Technology

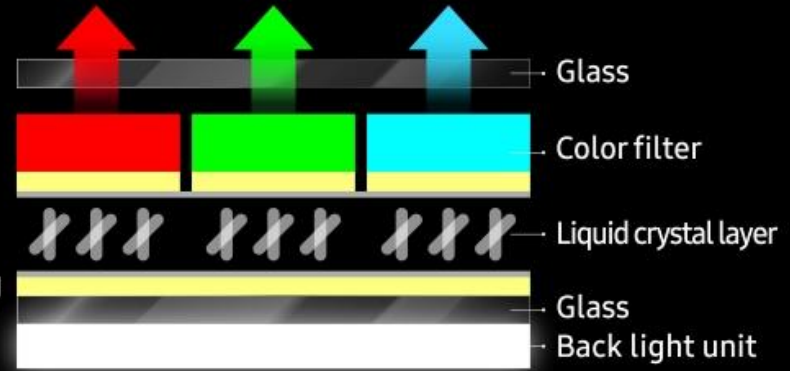


QD Applications: Display Technology

Structure of Quantum Dot and LCD Displays



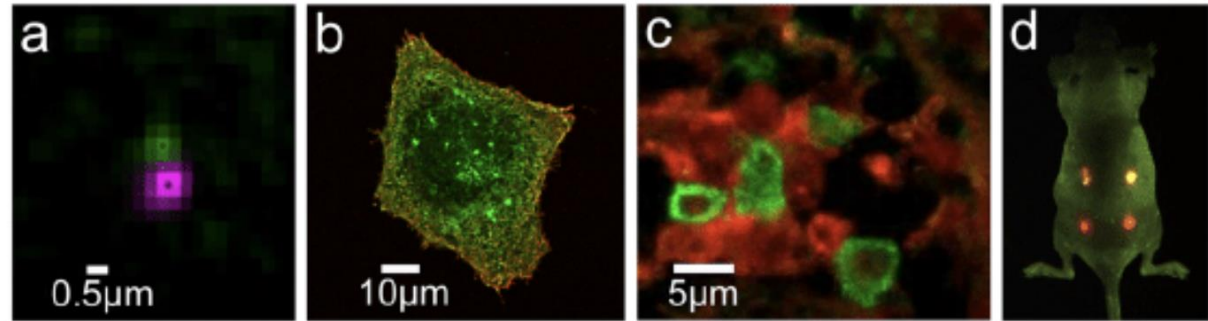
QD-OLED



LCD

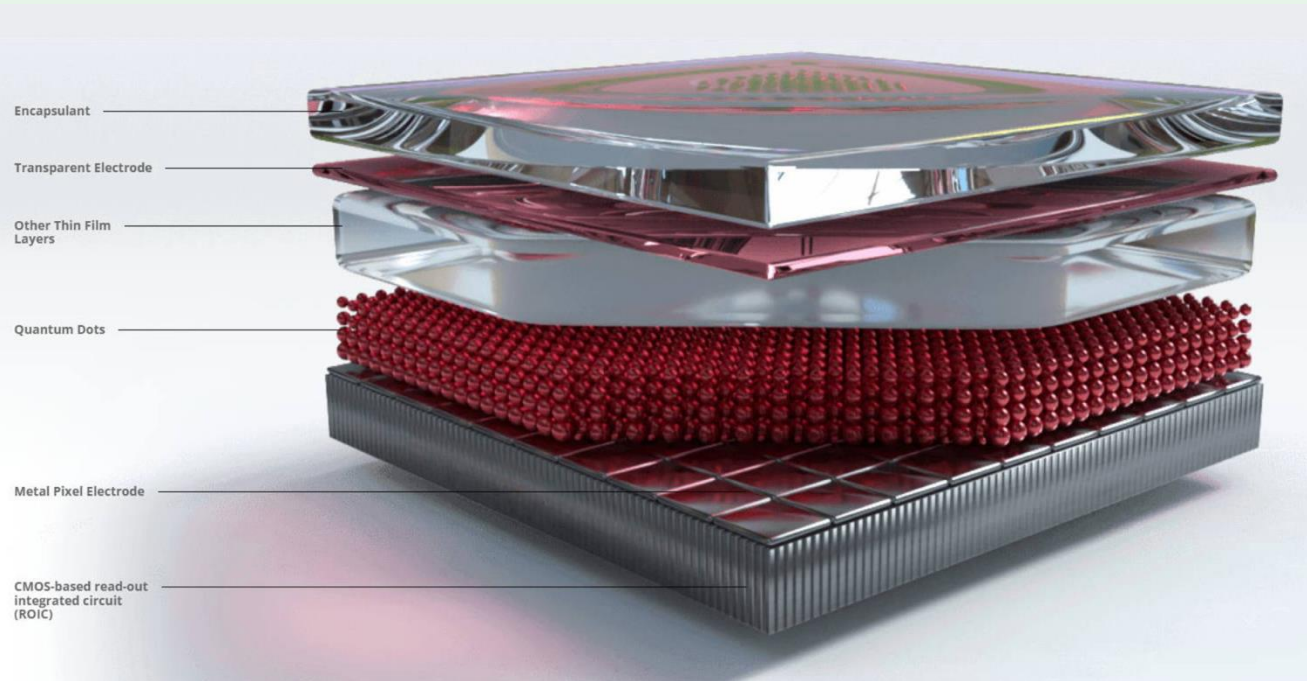
Credit: Samsung

QD Applications: Medical Imaging and Diagnostics



	Single Molecule	Single Cell	Tissue	In vivo
Modality	widefield confocal TIRF	widefield confocal TIRF	widefield confocal spectral imaging	whole animal intravital two-photon
Spatial resolution	nm	μm	μm	μm -mm
Temporal resolution	ms	ms-min	N/A	s-hr

QD Applications: Infrared Imaging



Credit: SWIR Vision

QD Applications: Infrared Imaging

Long-distance imaging through haze-filled sky

a. Google Pixel 4 Visible Image

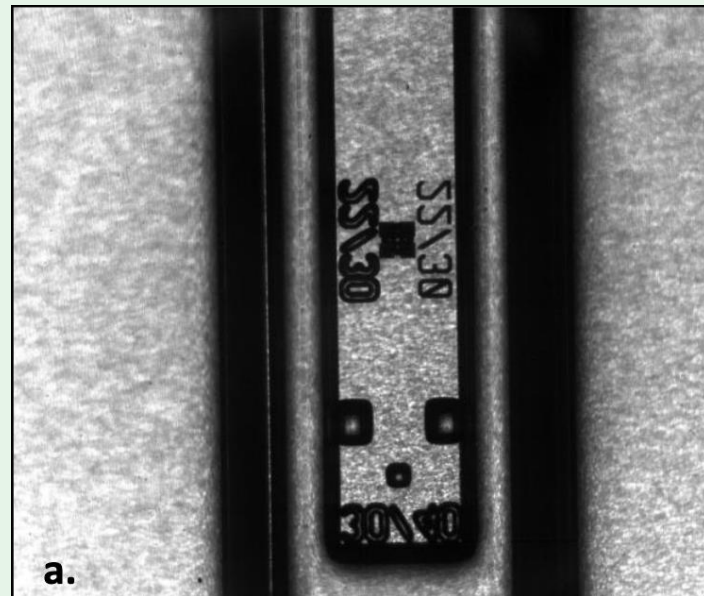


b. Acuros 1920 CQD SWIR Camera image



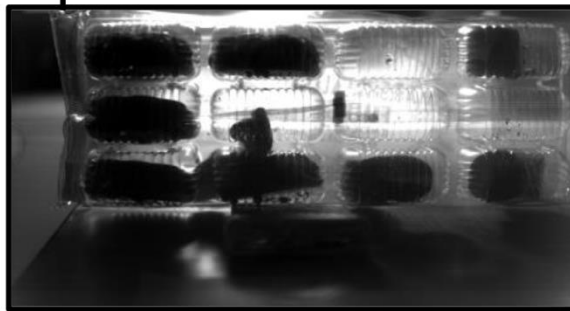
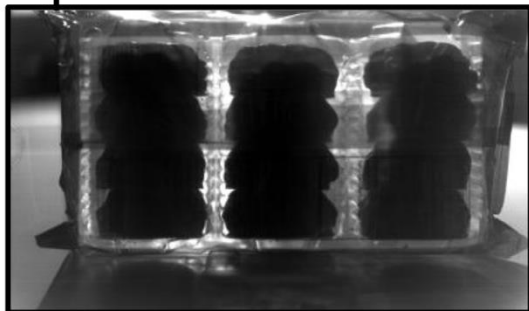
QD Applications: Infrared Imaging

Semiconductor wafer inspection



QD Applications: Infrared Imaging

Machine vision



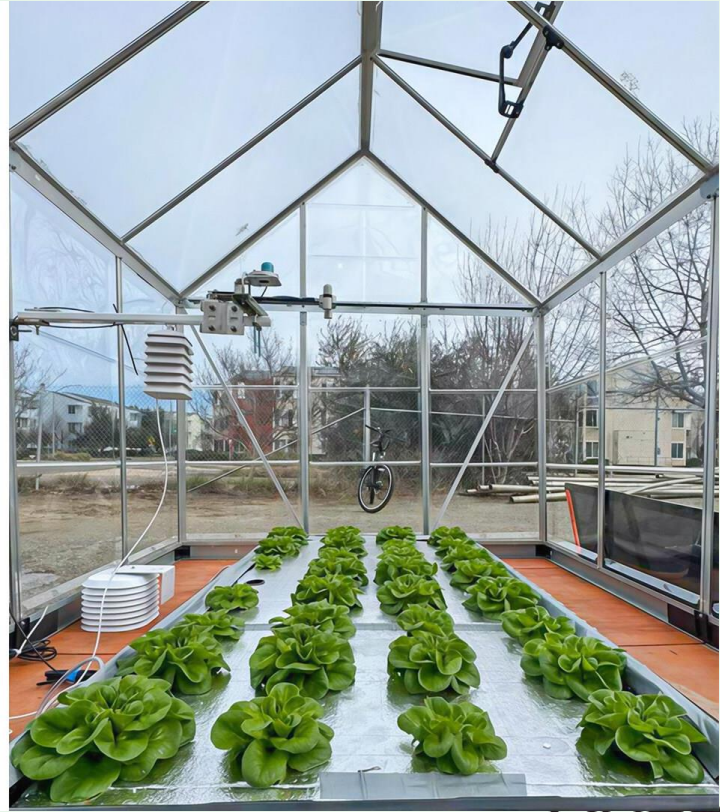
QD Applications: Infrared Imaging

Art restoration



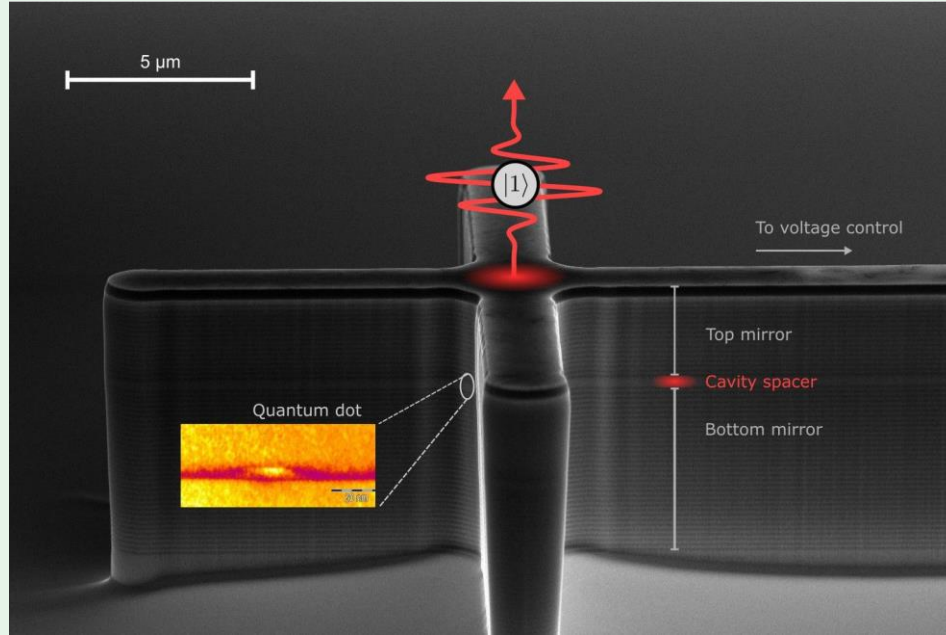
Credit: SWIR Vision

QD Applications: Agriculture



Other Emerging Applications

Single Photon Sources

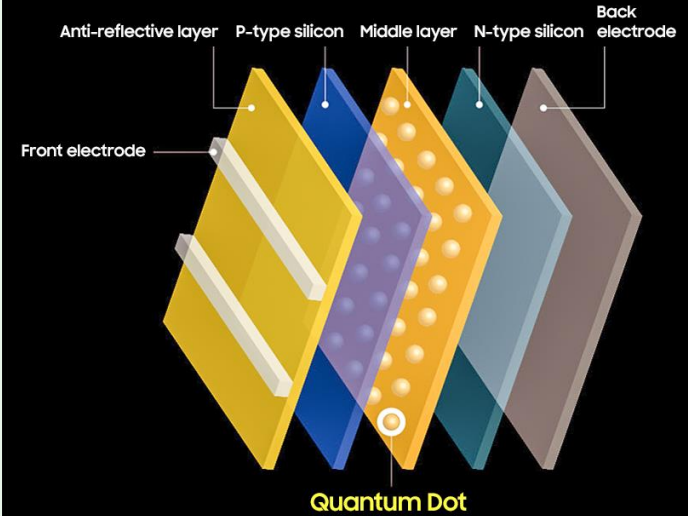


Credit: Quandela

Solar Cells

Structure of QD Solar Cell

It has a similar structure to traditional materials of solar cells in that excited electrons by light energy move on the surface electrodes, but are much thinner in thickness.



Credit: Samsung



Thanks

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Quantum Education

Materials developed by Quantum for All

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NSF #2048961 DRL (*Preparing Secondary Teachers and Students for Quantum Information Science*)

