Devil Physics
The Baddest Class on Campus
IB Physics

TSOKOS LESSON 12-1B: THE INTERACTION OF MATTER WITH RADIATION

Introductory Video

[Quantum Mechanics]

Essential Idea:

- The microscopic quantum world offers a range of phenomena, the interpretation and explanation of which require new ideas and concepts not found in the classical world.

Nature Of Science:

- Observations: Much of the work towards a quantum theory of atoms was guided by the need to explain the observed patterns in atomic spectra. The first quantum model of matter is the Bohr model for hydrogen.
- Paradigm shift: The acceptance of the wave–particle duality paradox for light and particles required scientists in many fields to view research from new perspectives.

Theory Of Knowledge:

- The duality of matter and tunnelling are cases where the laws of classical physics are violated.
- To what extent have advances in technology enabled paradigm shifts in science?

Understandings:

- Lsn 12-1A:
  - Photons
  - The photoelectric effect
  - Matter waves
  - Pair production and pair annihilation

Understandings:

- Lsn 12-1B:
  - Quantization of angular momentum in the Bohr model for hydrogen
  - The wave function
  - The uncertainty principle for energy and time and position and momentum
  - Tunneling, potential barrier and factors affecting tunneling probability

Applications And Skills:

- Discussing the photoelectric effect experiment and explaining which features of the experiment cannot be explained by the classical wave theory of light
- Solving photoelectric problems both graphically and algebraically

Applications And Skills:

- Discussing experimental evidence for matter waves, including an experiment in which the wave nature of electrons is evident
- Stating order of magnitude estimates from the uncertainty principle

Guidance:

- The order of magnitude estimates from the uncertainty principle may include (but is not limited to) estimates of the energy of the ground state of an atom, the impossibility of an electron existing within a nucleus, and the lifetime of an electron in an excited energy state
- Tunnelling to be treated qualitatively using the idea of continuity of wave functions

Data Booklet Reference:

- $E = hf$
- $E_{max} = hf - \Phi$
- $E = -\frac{13.6}{n^2} eV$
- $mvr = \frac{nh}{2\pi}$
- $P(r) = |\psi|^2 \Delta V$
- $\Delta x \Delta p \geq \frac{h}{4\pi}$
- $\Delta E \Delta t \geq \frac{h}{4\pi}$

Utilization:

- The electron microscope and the tunnelling electron microscope rely on the findings from studies in quantum physics
- Probability is treated in a mathematical sense in Mathematical studies SL sub-topics 3.6–3.7

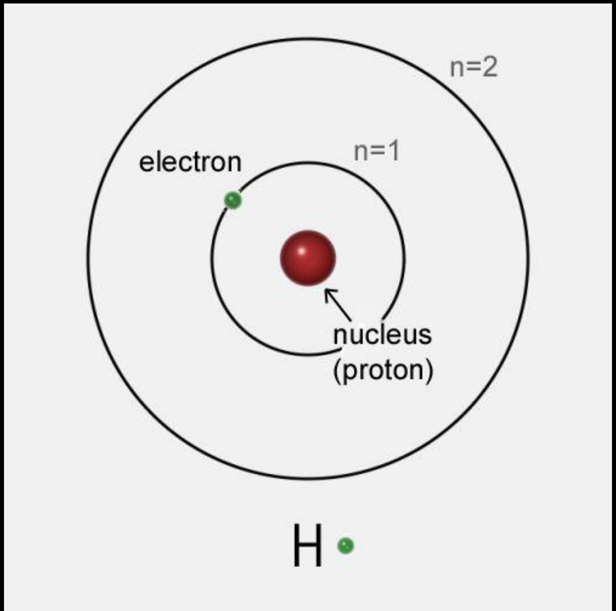
Aims:

- Aim 1: study of quantum phenomena introduces students to an exciting new world that is not experienced at the macroscopic level. The study of tunneling is a novel phenomenon not observed in macroscopic physics.

Aims:

- Aim 6: the photoelectric effect can be investigated using LEDs
- Aim 9: the Bohr model is very successful with hydrogen but not of any use for other elements

Quantization of Angular Momentum

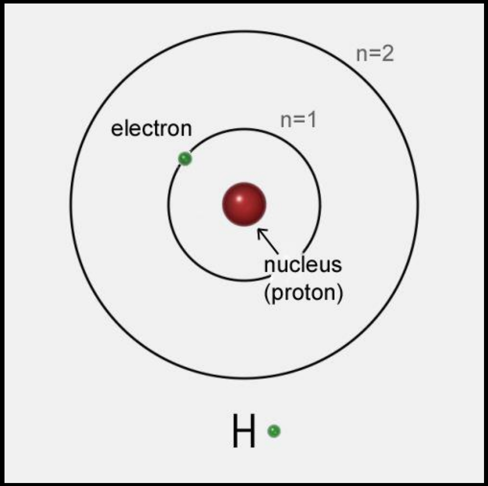


- Bohr Model of the Atom
  - Hydrogen atom
  - Electron orbits the nucleus
  - Total energy of the electron is

$$E_T = KE + PE$$

$$E_T = \frac{1}{2}mv^2 + \left(-\frac{ke^2}{r}\right)$$

Quantization of Angular Momentum



- Bohr Model of the Atom
  - Electrical force provides the centripetal force which allows the electron to remain in orbit

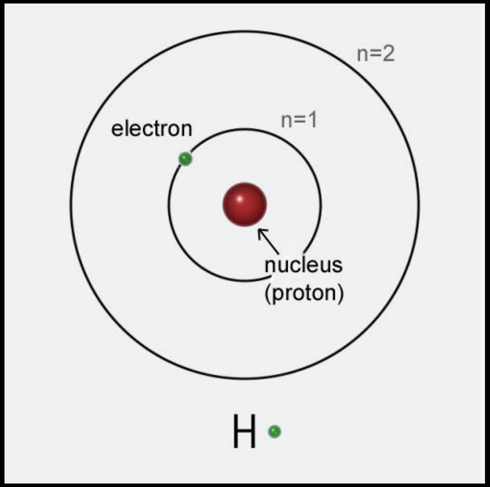
$$k\frac{qq}{r^2} = m\frac{v^2}{r}$$

$$\frac{ke^2}{r^2} = \frac{mv^2}{r}$$

$$\frac{ke^2}{r} = mv^2$$

Quantization of Angular Momentum

- Bohr Model of the Atom
  - By substituting



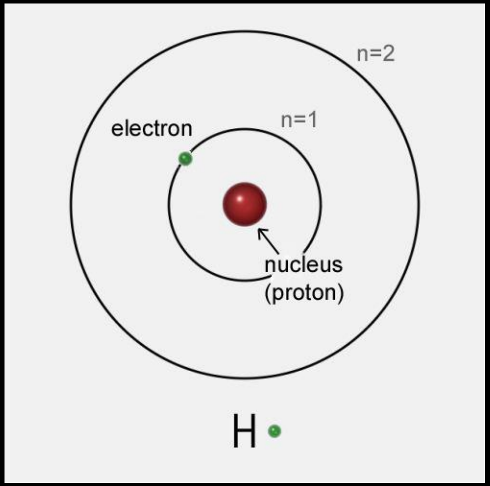
$$\frac{ke^2}{r} = mv^2$$

$$E_T = \frac{1}{2}\frac{ke^2}{r} - \frac{ke^2}{r}$$

$$E_T = -\frac{1}{2}\frac{ke^2}{r}$$

Quantization of Angular Momentum

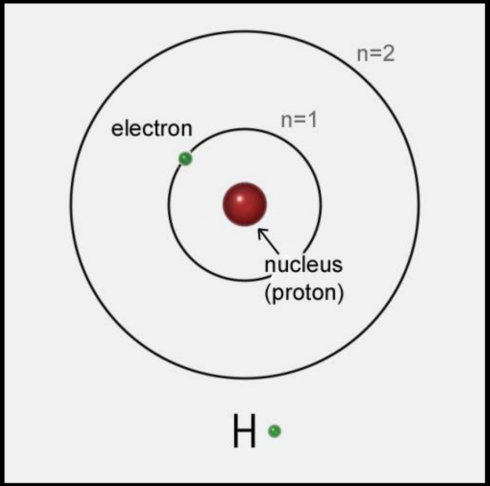
- Bohr Model of the Atom
  - For any given radius of the electron, there exists a discrete value of the electron's energy
  - Bohr then made the assumption that angular momentum (***L* = *mvr***) is quantized



$$E_T = -\frac{1}{2}\frac{ke^2}{r}$$

$$mvr = \frac{nh}{2\pi}$$

Quantization of Angular Momentum



- Bohr Model of the Atom
  - From these he derived an equation for the ***quantization of electron energy***
  - This explained the emission and absorption spectra of atoms

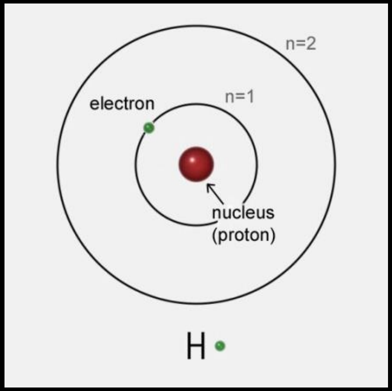
$$E_T = -\frac{1}{2}\frac{ke^2}{r}$$

$$mvr = \frac{nh}{2\pi}$$

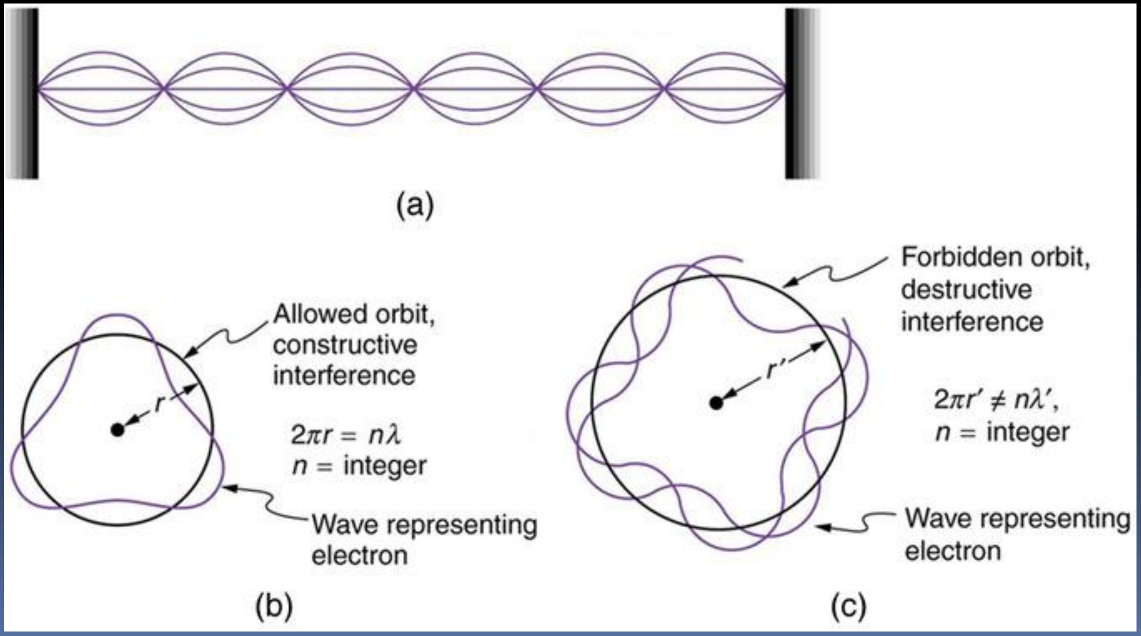
$$\frac{ke^2}{r} = mv^2$$

$$E = -\frac{13.6}{n^2} eV$$

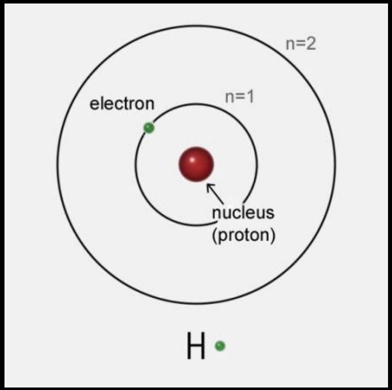
Quantization of Angular Momentum



- Bohr Model of the Atom
  - Discrete energy levels means discrete values of orbit radii
  - If the electron were to travel in a wave, the wavelength must have constructive interference over the distance of the circumference



Quantization of Angular Momentum



- Bohr Model of the Atom

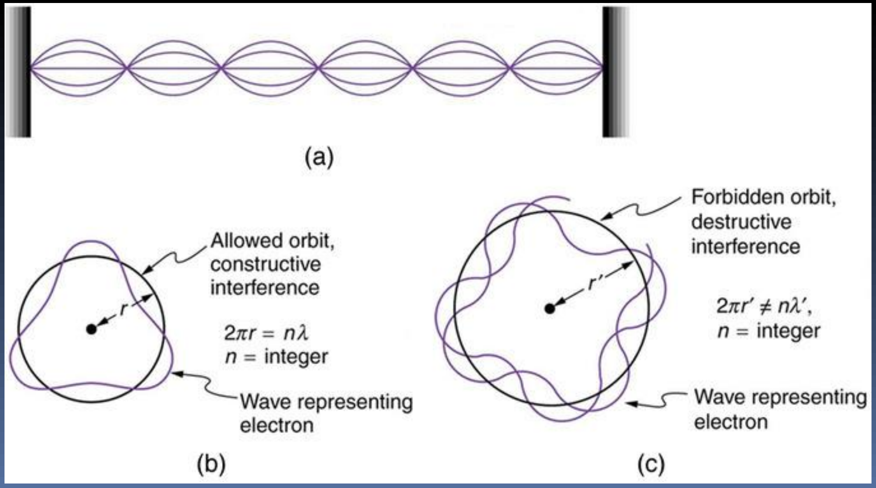
$$mvr = \frac{nh}{2\pi}$$

$$2\pi r = \frac{nh}{mv}$$

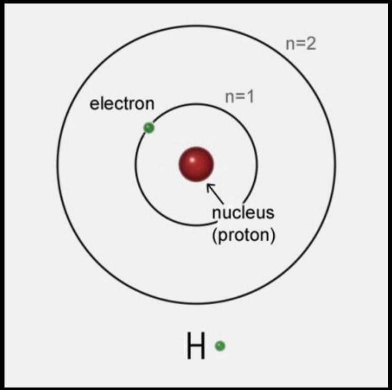
$$\lambda = \frac{h}{mv}$$

$$2\pi r = n\lambda$$

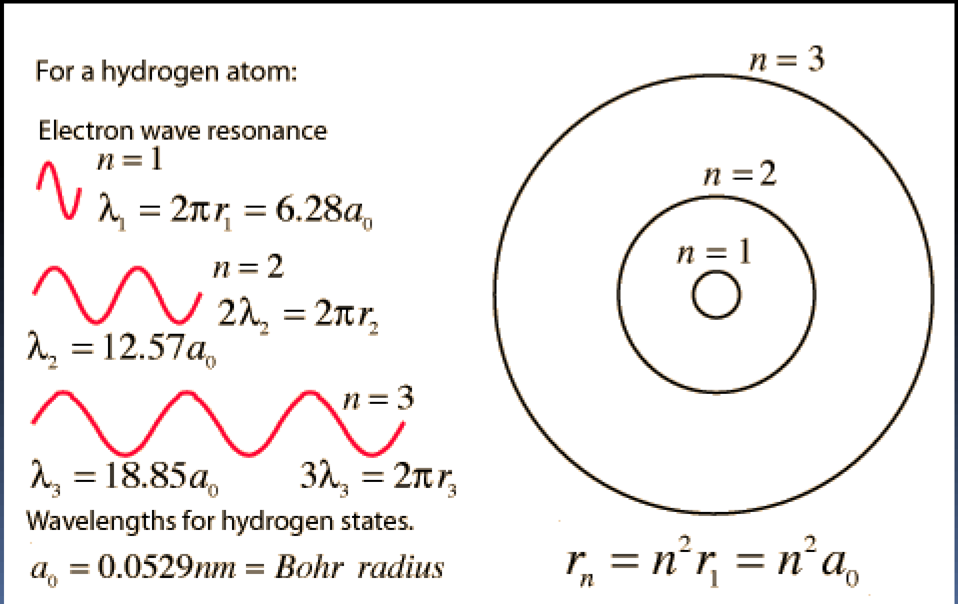
  - Discrete energy levels means discrete values of orbit radii
  - If the electron were to travel in a wave, the wavelength must have constructive interference over the distance of the circumference



Quantization of Angular Momentum



- Bohr Model of the Atom
  - This equates to a standing wave along the circumference of the orbit.
  - Standing waves do not transmit energy.
  - Electrons do not emit energy when in allowed orbits



Wavefunction

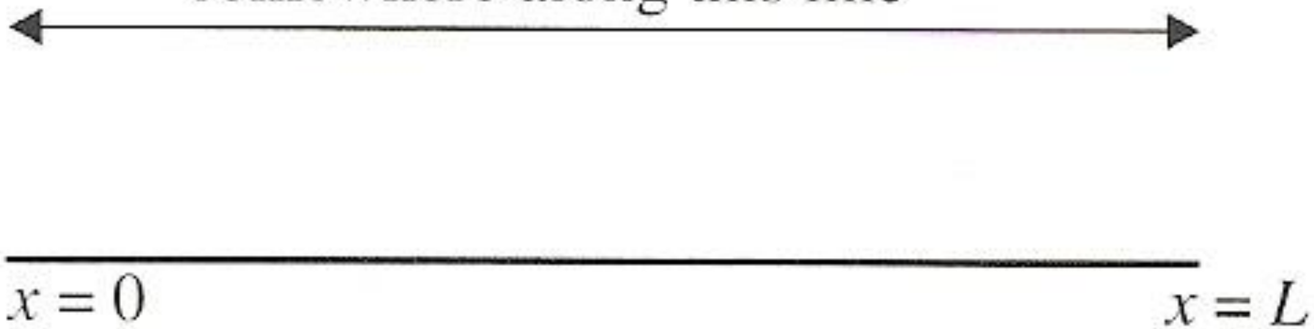
- Matter waves – particles exhibit wave-like behavior
- Electrons exist as standing waves along the circumference of their orbits

Electron In A Box

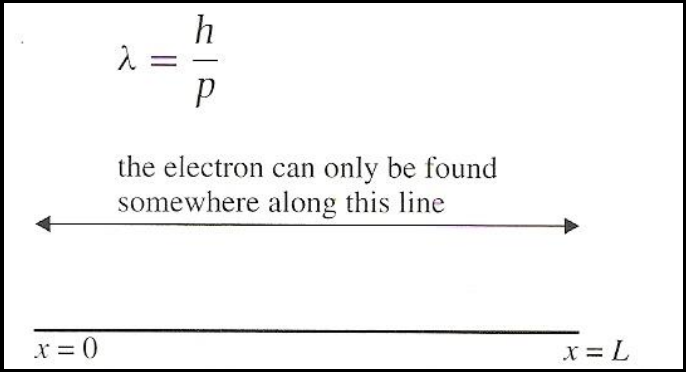
$$\lambda = \frac{h}{p}$$

de Broglie Wavelength

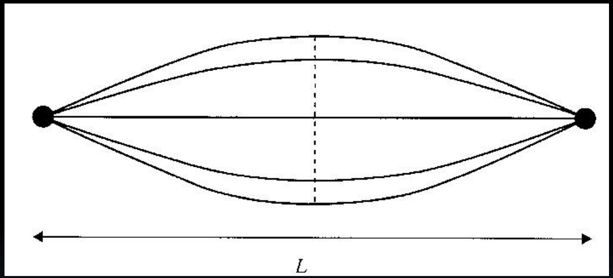
the electron can only be found somewhere along this line



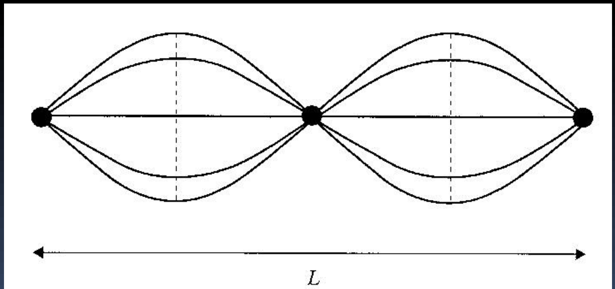
Electron In A Box

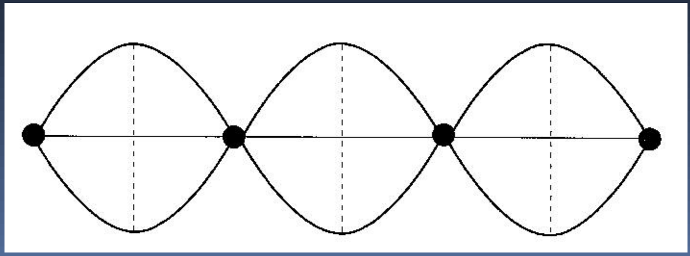


- Amplitude is zero at ends of the box
- Since electron can't lose energy, the wave in the box is a standing wave with fixed nodes at x = 0 and x = L



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



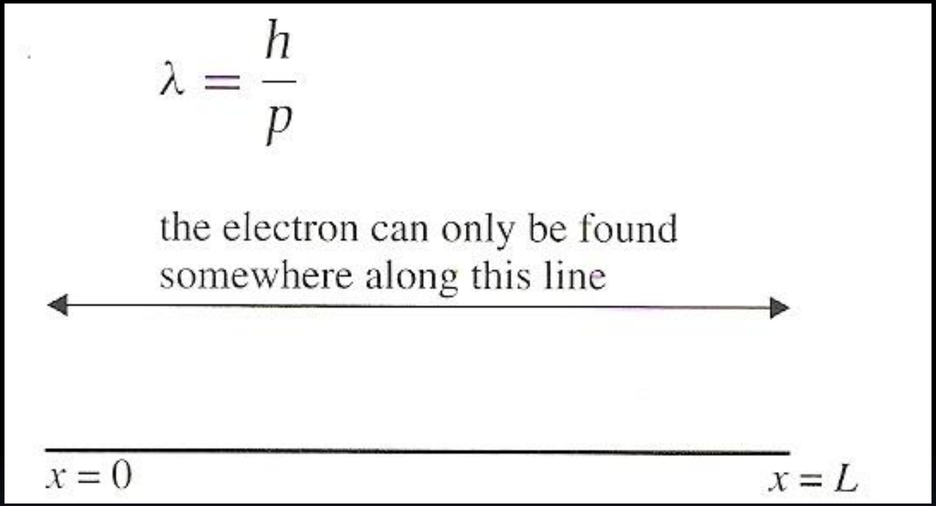


Electron In A Box

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

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

$$p = \frac{hn}{2L}$$

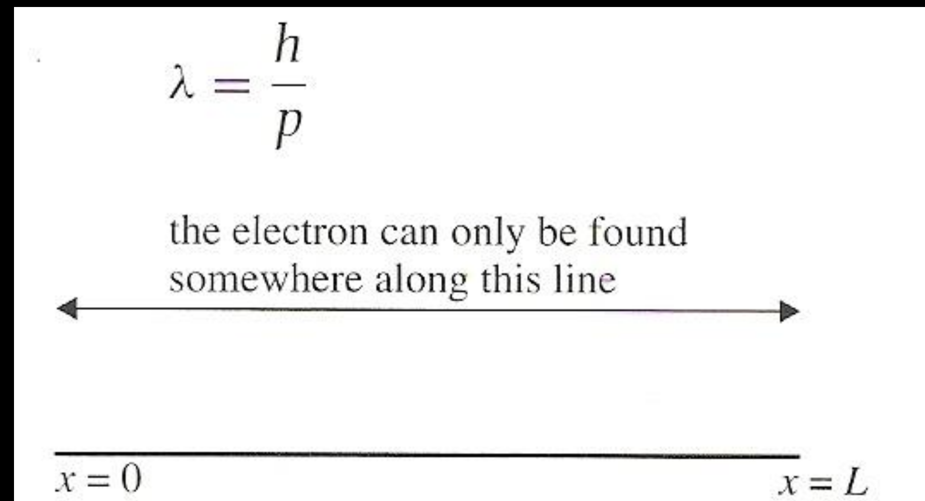


Electron In A Box

$$p = \frac{hn}{2L}$$

$$E_k = \frac{p^2}{2m}$$

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



- The result is that electron energy is always a multiple of a discrete or quantized value
- The same principle applies for electrons surrounding a nucleus

Schrödinger Theory

- Wave Function, $\Psi(x,t)$
- Schrodinger equation for hydrogen
- Separate equations for electrons in every type of atom
- Result is that the energy of an electron in a specific atom is ***quantized***

Figure 5.5 Erwin Schrödinger.

Schrödinger Theory

- Schrodinger's Theory applied to the electron in a box model yields the following data for a hydrogen atom
- Energy is discrete or quantized to one of the ***energy levels*** given by n = 1, 2, 3

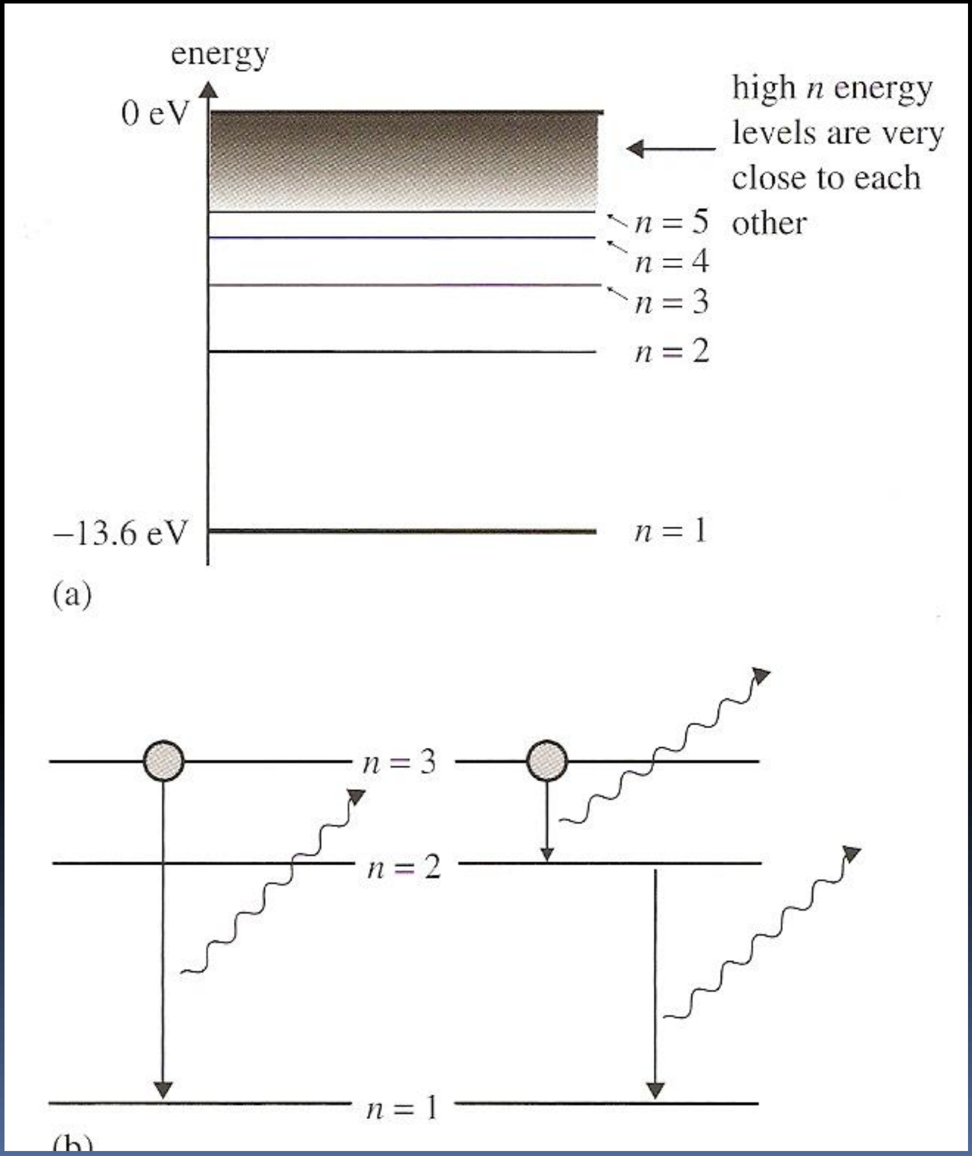
$$E = -\frac{C}{n^2}$$

$$C = \frac{2\pi^2 m e^4 k^2}{h^2}$$

$$E = -\frac{13.6}{n^2} eV$$

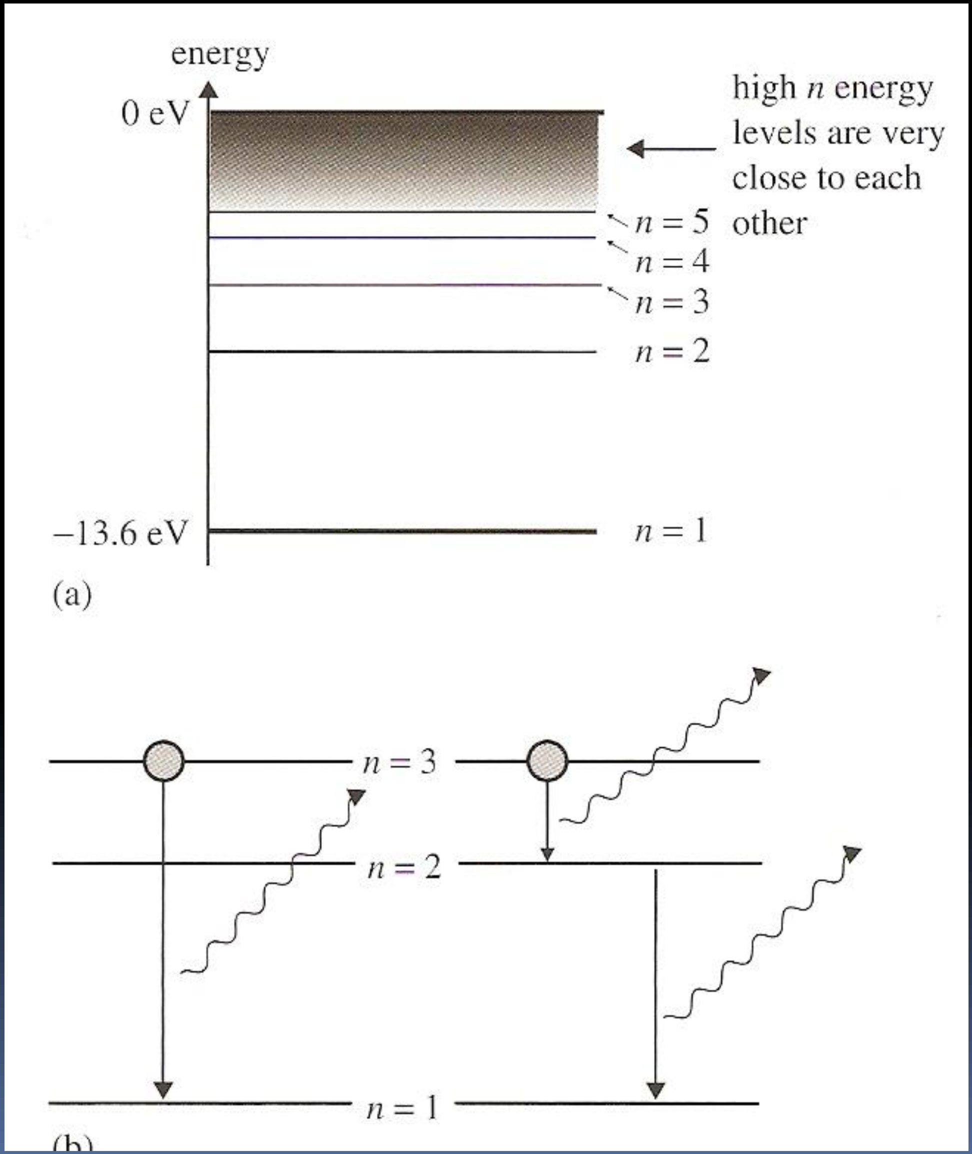
Schrödinger Theory

- Energy levels of emitted photons correspond to energy level changes of electrons
- Each time an electron drops in energy level, a photon is released with that energy

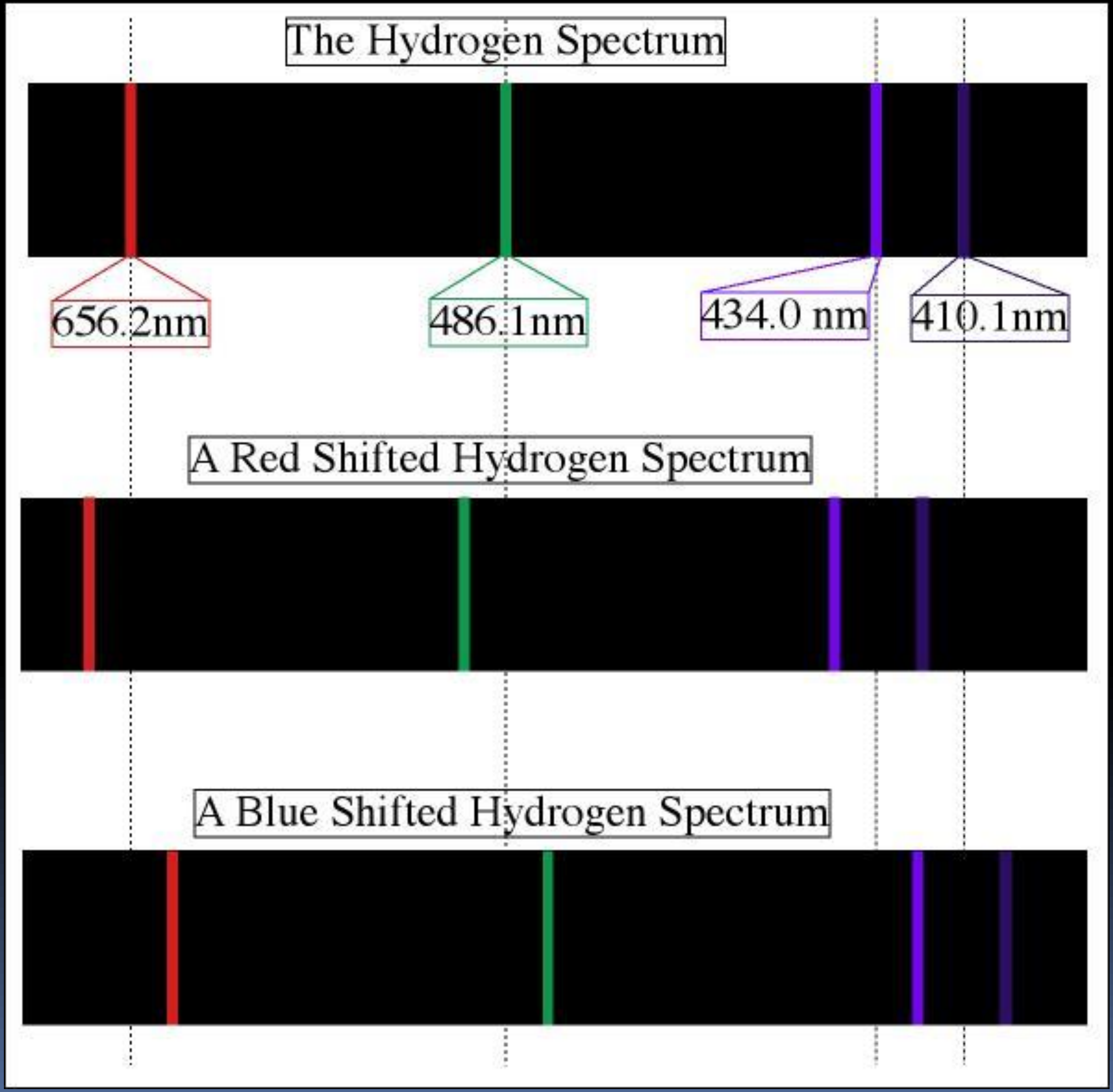


Schrödinger Theory

- Since E = hf, the photon will have a discrete frequency according to its energy
- Knowing the energy level change of the electron, we can compute the frequency and vice versa



Atomic Spectra



- Different gases will have emission lines at different wavelengths
- Wavelengths emitted are unique to each gas

Schrödinger Theory
Max Born Interpretation

- Schrödinger gave the potential location of an electron at any given time
- Max Born gave the probability of the electron's position within a given volume, ΔV

$$P(x,t) = |\Psi(x,t)|^2 \Delta V$$

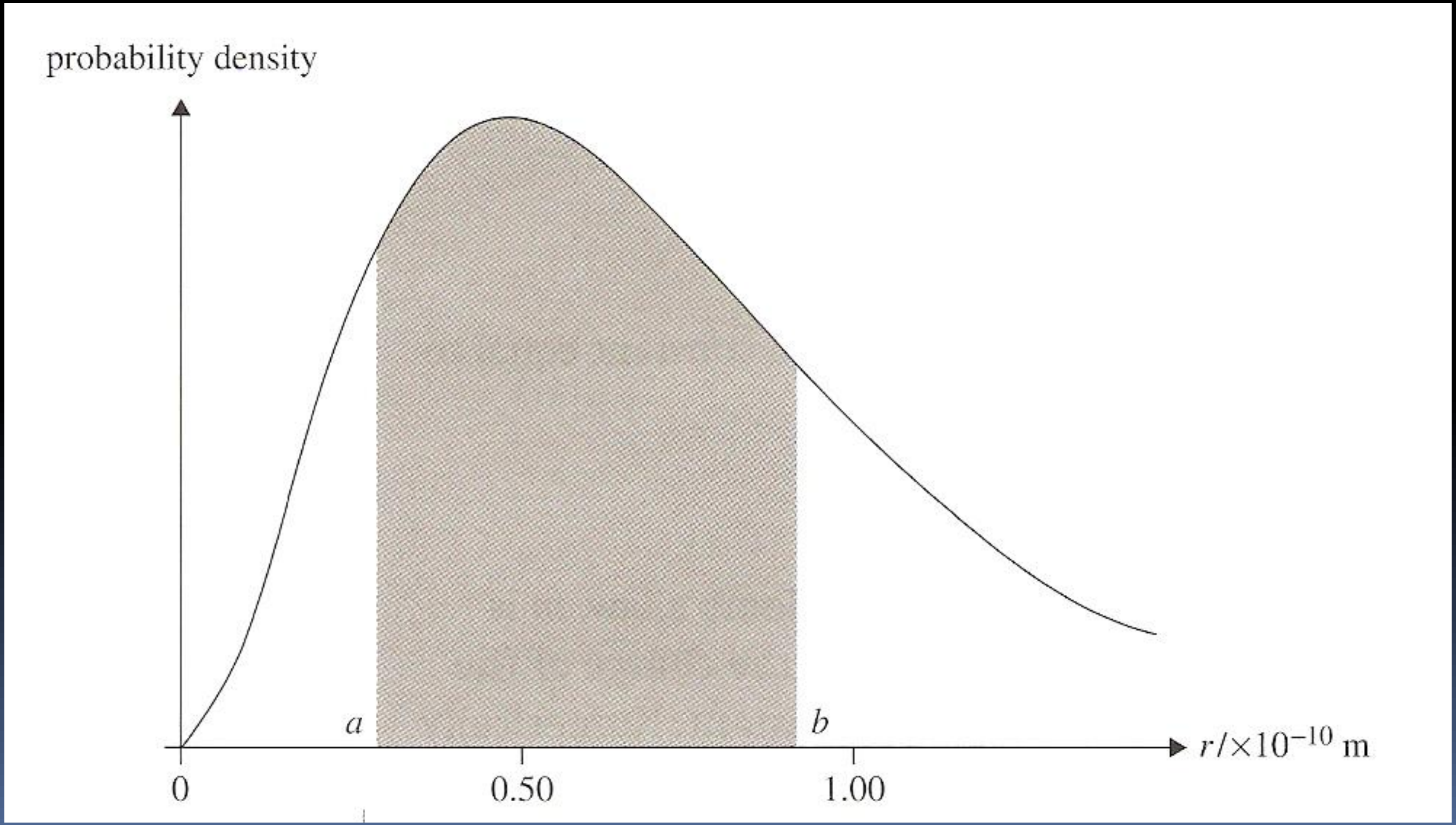
- will give the ***probability*** that an electron will be ***near*** position x at time t

Schrödinger Theory

- Schrodinger's Theory applied to electrons in a hydrogen atom produced the same values that Bohr derived
- The end result is a probability wave – a wave that gives the probability of finding a particle near a particular position

Schrödinger Theory

- Schrodinger's Theory also predicts the probability that a transition will occur ($|\Psi(x,t)|^2$)
- Explains why some spectral lines are brighter



Heisenberg Uncertainty Principle

- Applied to position and momentum:
- Basis is the wave-particle duality and Schrödinger 's wave function
- Can't clearly explain behavior based on wave theory or classical mechanics

Figure 5.8 Werner Heisenberg.

Heisenberg Uncertainty Principle

- It is not possible to ***simultaneously*** determine the position and momentum of something with indefinite precision

$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

Figure 5.8 Werner Heisenberg.

Heisenberg Uncertainty Principle

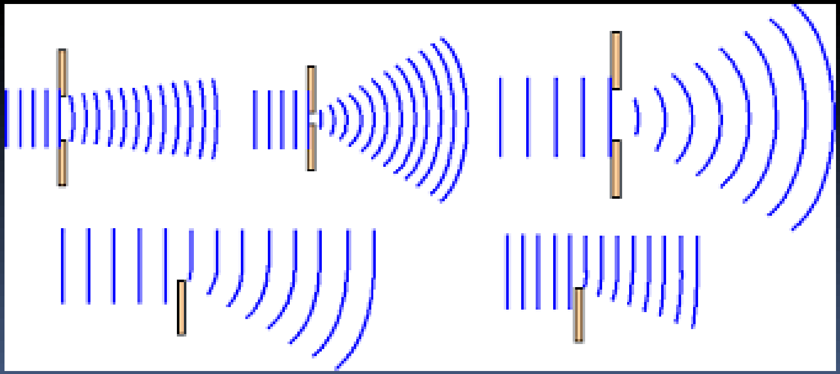
$$\Delta x \Delta p \geq \frac{h}{4\pi}$$

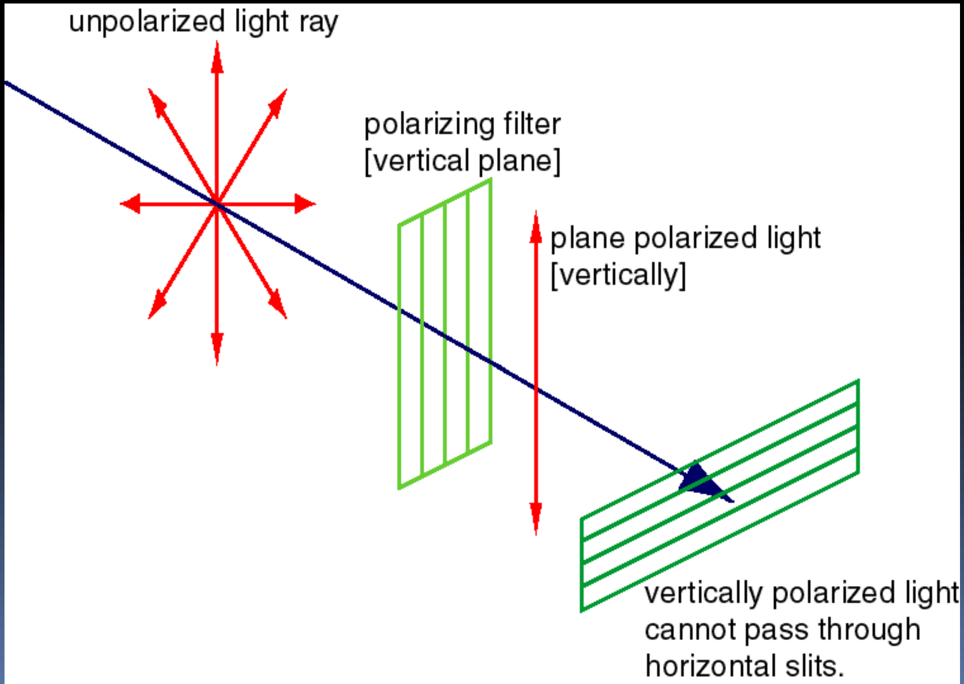
- Making momentum accurate makes position inaccurate and vice versa
  - As Δp approaches 0, Δx approaches infinity
  - As Δx approaches 0, Δp approaches infinity

Figure 5.8 Werner Heisenberg.

Heisenberg Uncertainty Principle

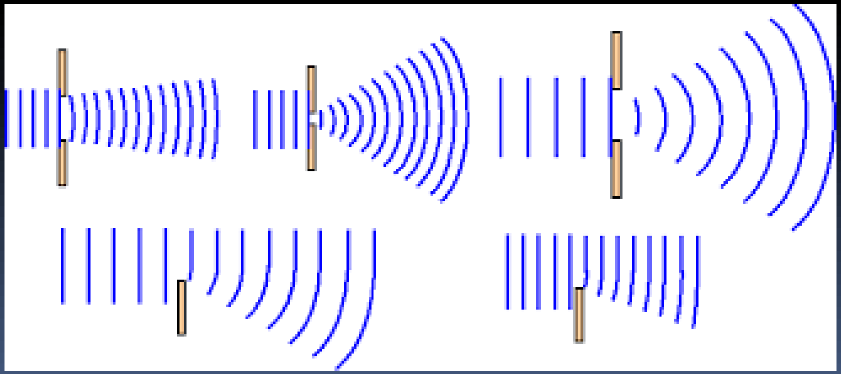
- Think of aiming a beam of electrons through a thin slit
- Like polarization, we limit wave passage through the slit to a vertical plane
- However, the wave will diffract which changes the horizontal position

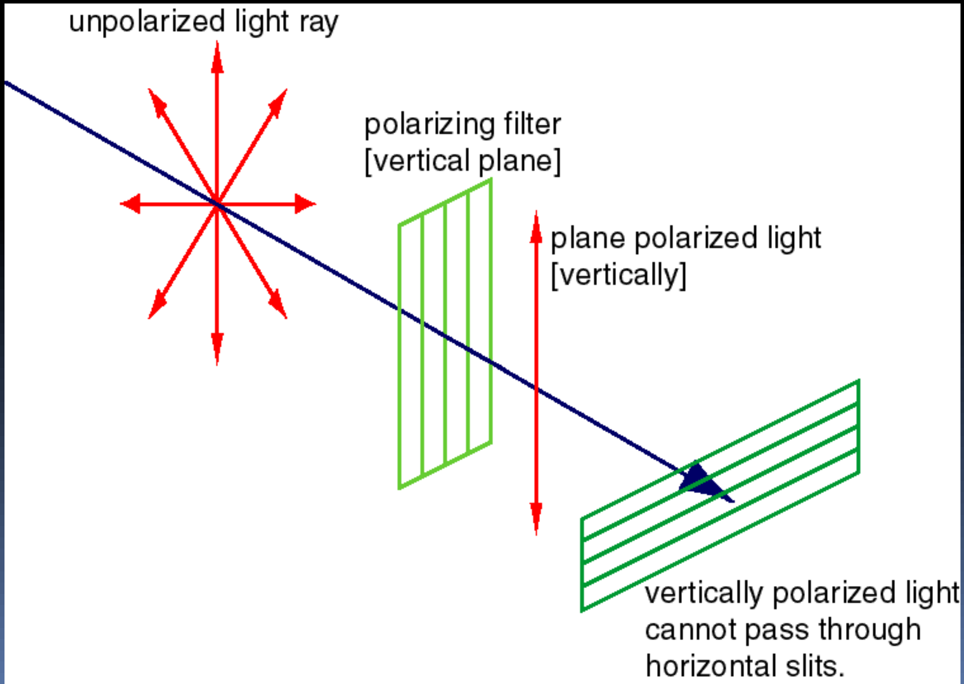




Heisenberg Uncertainty Principle

- Even though vertical position is fairly certain, change in horizontal position means a change in momentum because of the change in the horizontal component of the velocity





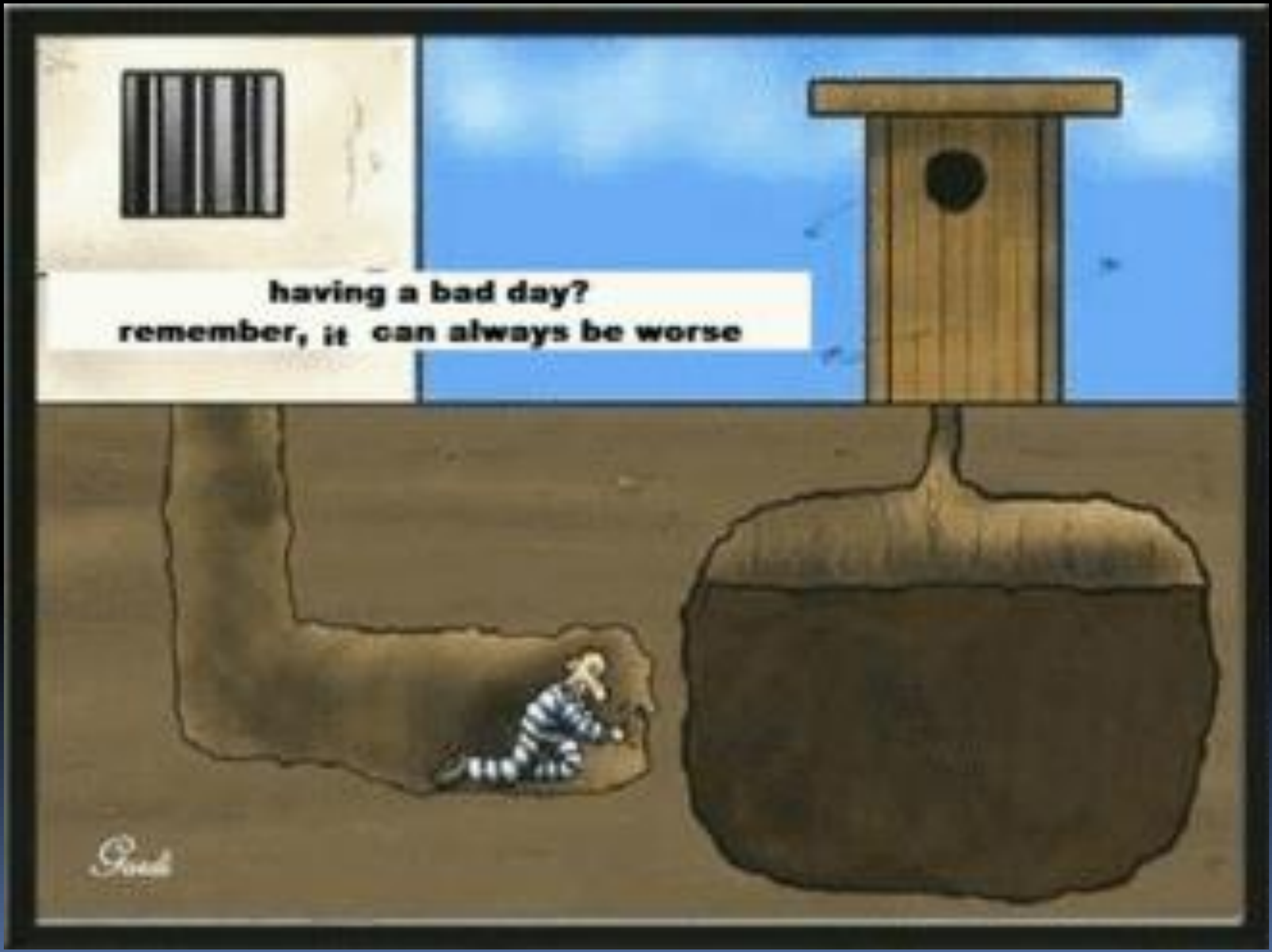
Heisenberg Uncertainty Principle

- Applied to energy and time:
- The same principle can be applied to energy versus time

$$\Delta E \Delta t \geq \frac{h}{4\pi}$$

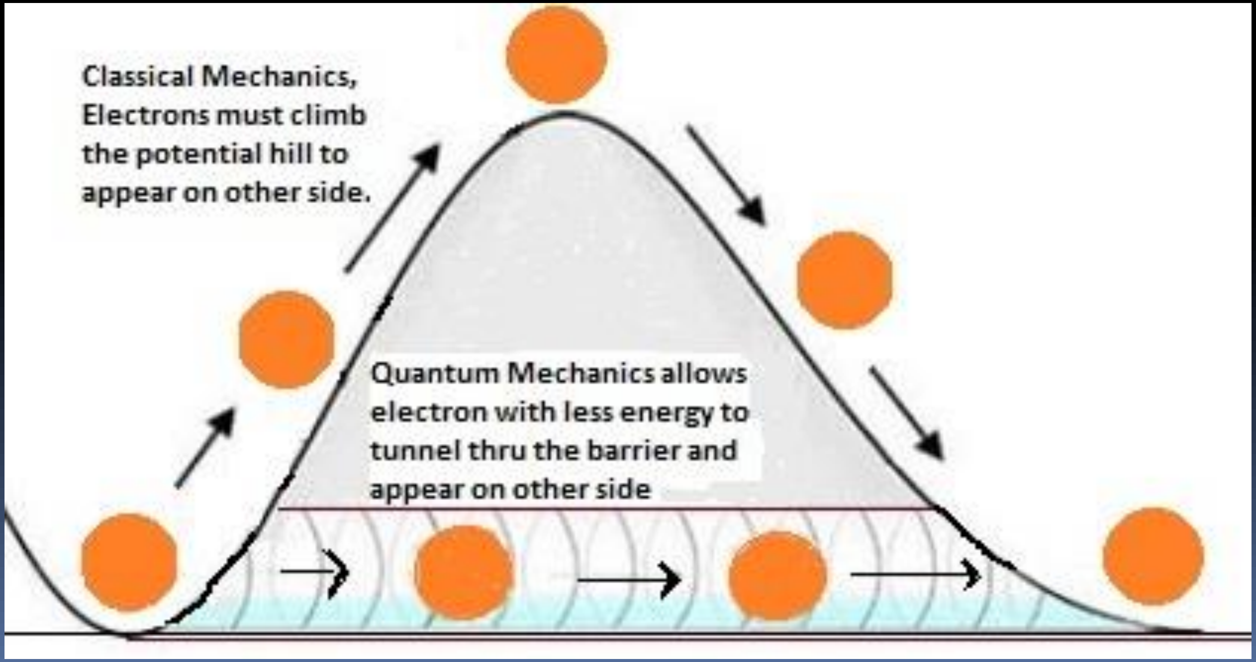
Figure 5.8 Werner Heisenberg.

Tunneling



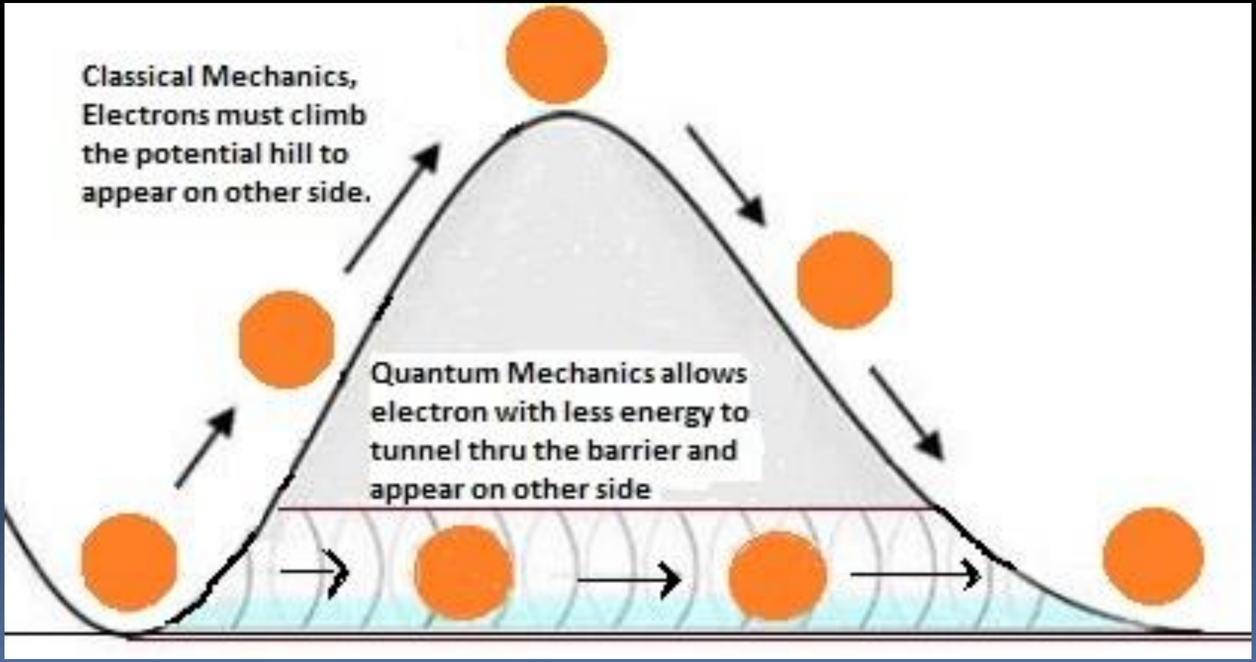
Tunneling

- Classical Mechanics
  - To get over a hill, a ball must have a kinetic energy at the bottom greater than its potential energy at the top
  - If it doesn't, you don't expect to find it on the other side
  - The hill acts as a ***"potential barrier"***



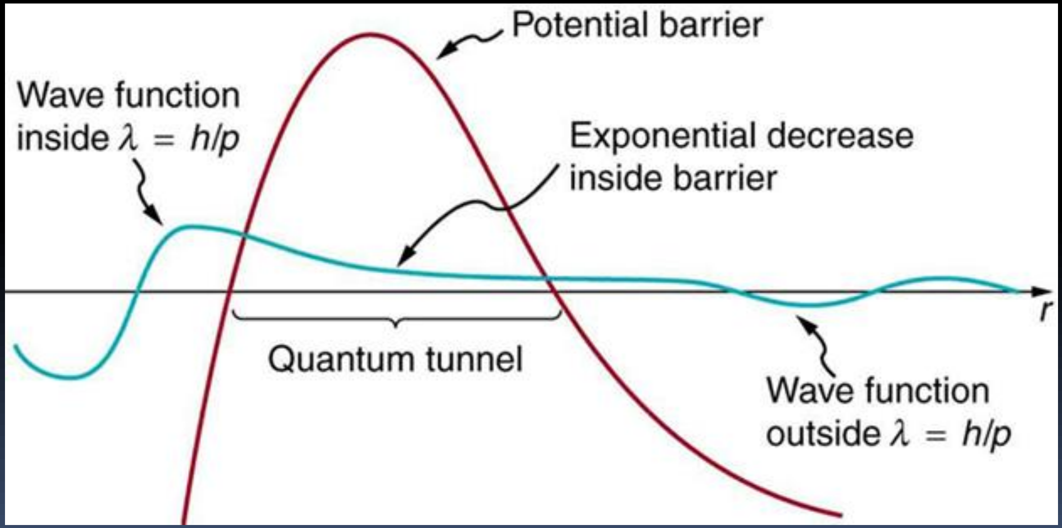
Tunneling

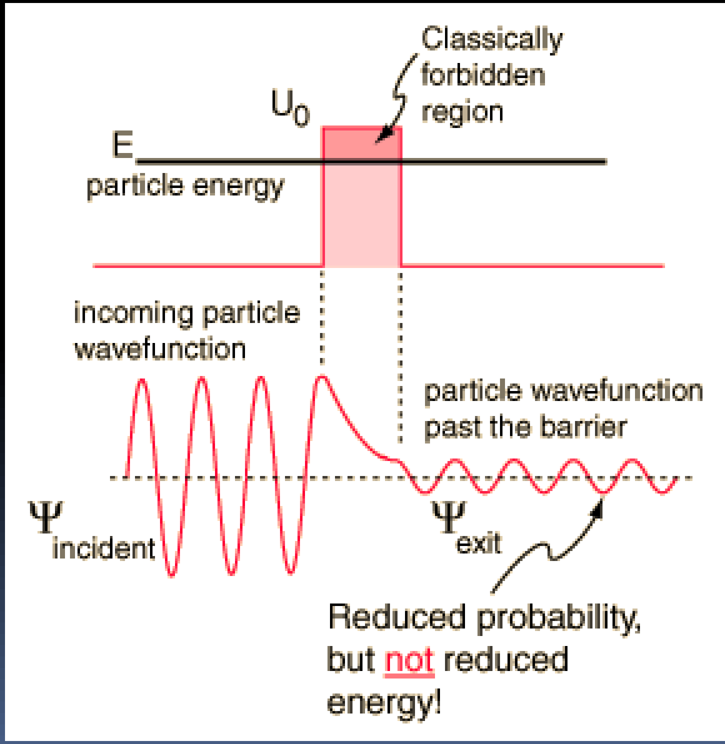
- Quantum Mechanics
  - Quantum mechanics allows a particle to appear on the other side of a barrier because of the wave properties of the particle



Tunneling

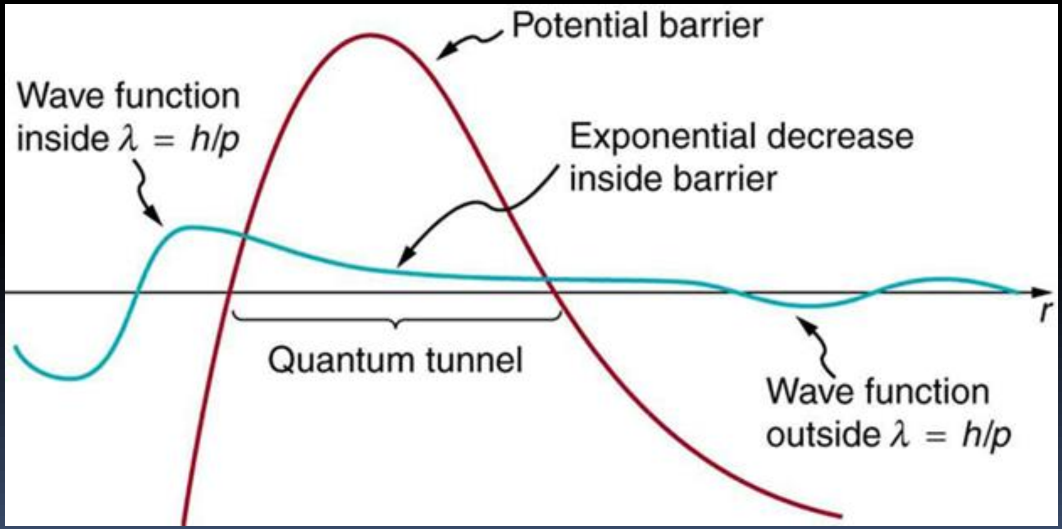
- Quantum Mechanics
  - Prior to the barrier, a standing wave exists with superposition of reflected particles and a high probability of finding a particle

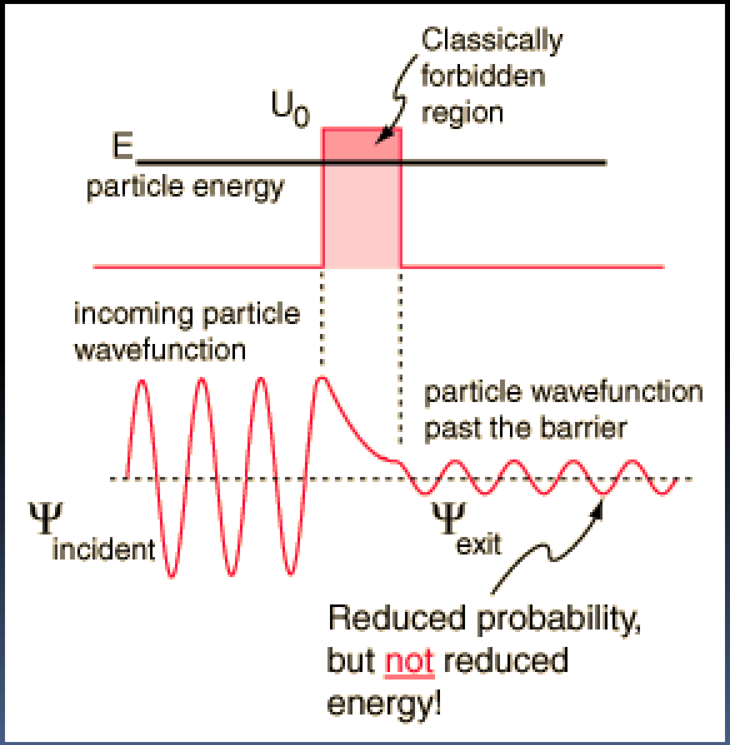




Tunneling

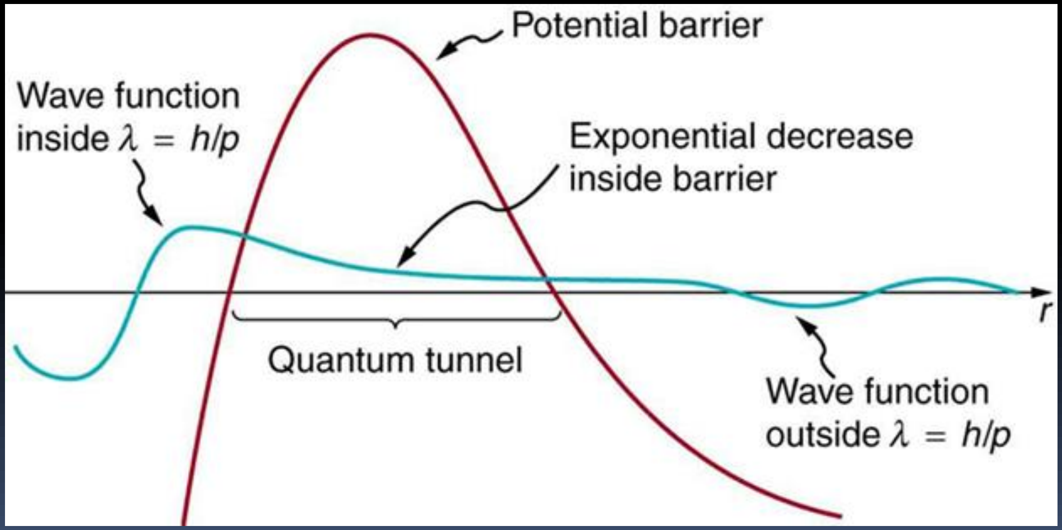
- Quantum Mechanics
  - When tunneling through the barrier, the probability decreases exponentially

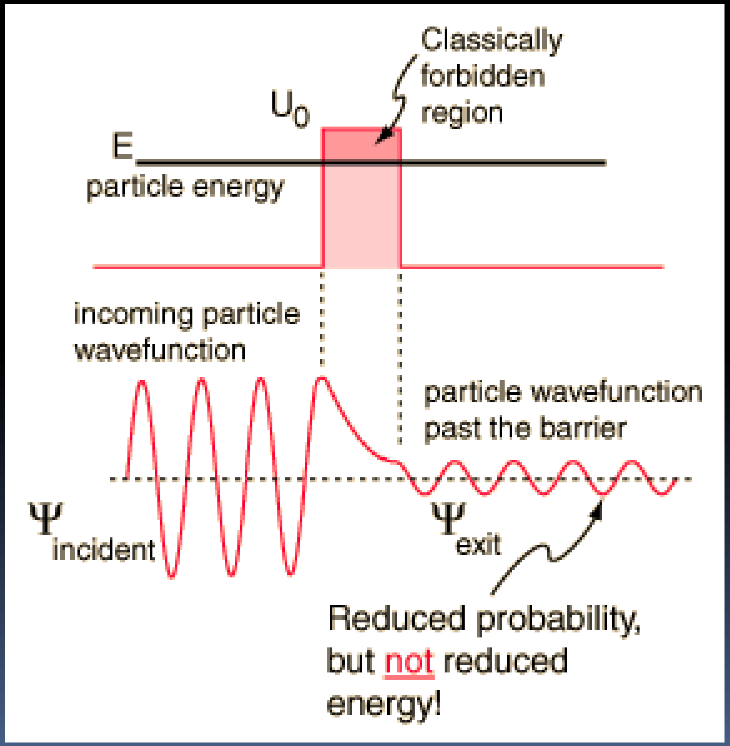




Tunneling

- Quantum Mechanics
  - On the other side of the barrier, the probability of finding a particle is greatly reduced, but the energy of the particle is the same as before the barrier!

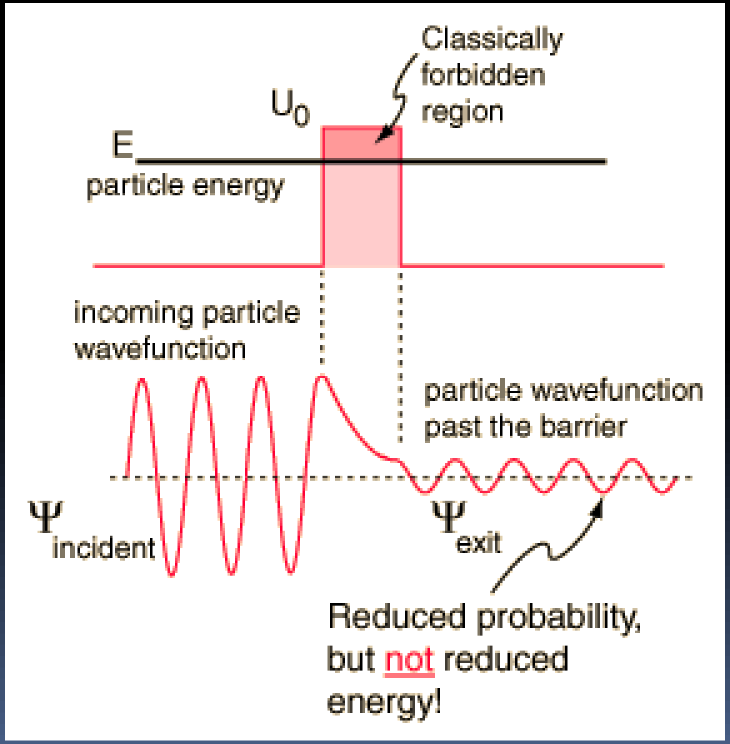




Tunneling

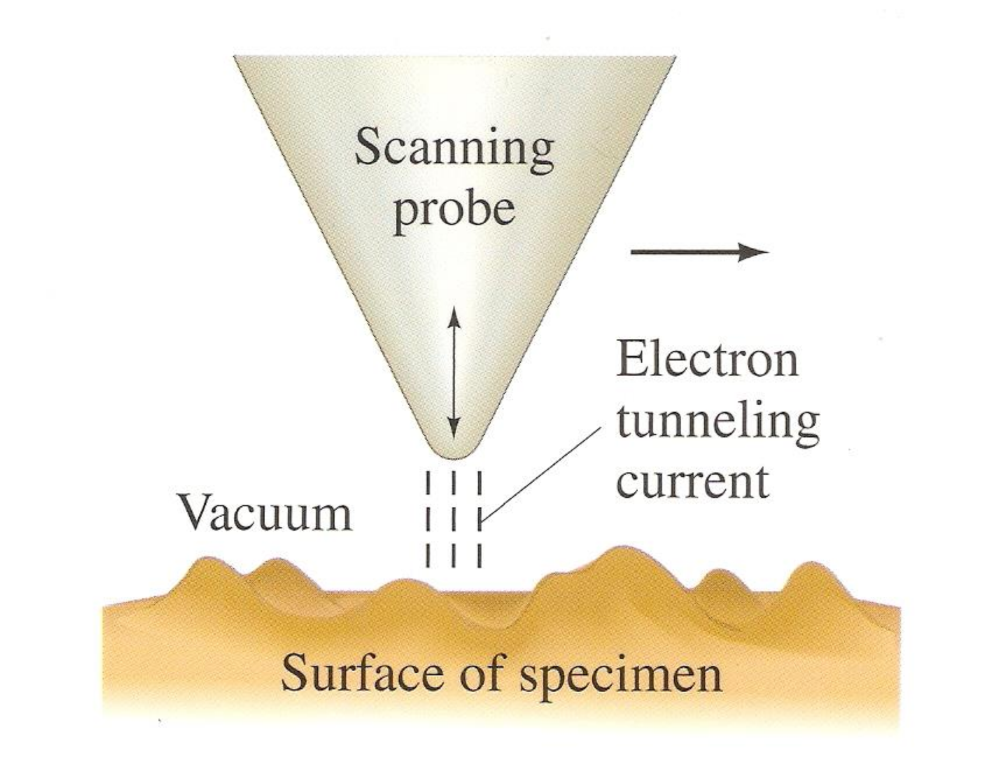
- Factors Affecting Transmission Probability
  - Mass of the particles
  - Width of the barrier
  - Difference between the energy of the barrier and that of the particle

$$p \propto e^{-w\sqrt{m\Delta E}}$$



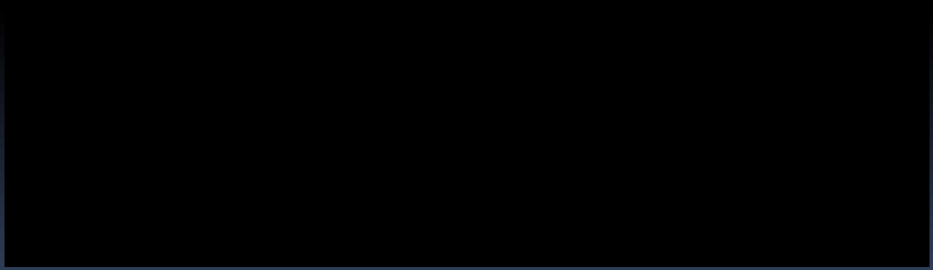
Tunneling

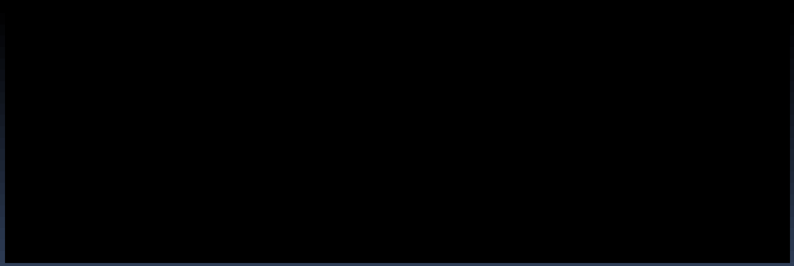
- Applications:
  - Scanning Tunneling Electron Microscope that can 'see' atoms



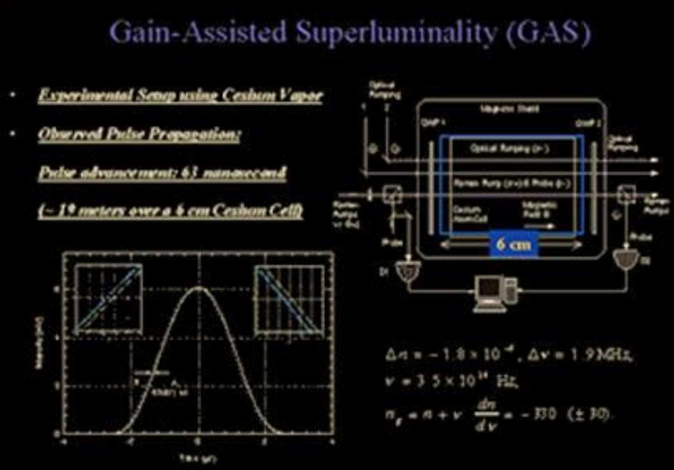
Tunneling

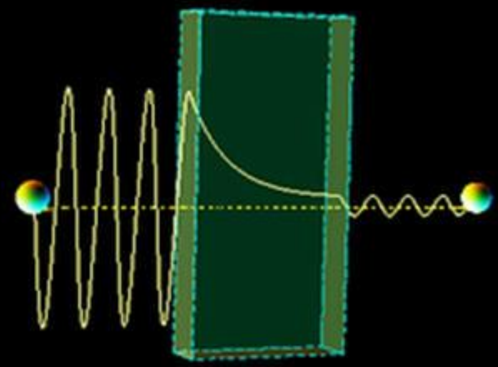
- Applications:
  - Cool Hockey Pucks times 2

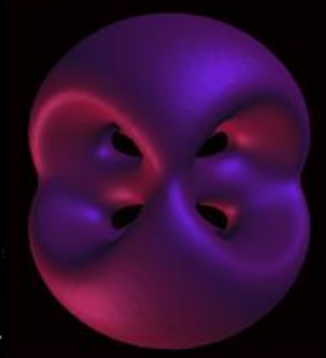




Quantum Tunneling







- Effect: QUANTUM
- Speed: SUBLUMINAL
- Special Spacetime Geometry: NO
- ✔ Time Travel to Future: YES
- ✘ Time Travel to Past: NO
- ✘ Matter Transport: NO
- ✔ Information Transport: YES
- ✔ Technically Viable: YES
- ✔ Possible w/o Exotic Materials: YES
- ✔ Low Input Power: YES

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- The order of magnitude estimates from the uncertainty principle may include (but is not limited to) estimates of the energy of the ground state of an atom, the impossibility of an electron existing within a nucleus, and the lifetime of an electron in an excited energy state
- Tunnelling to be treated qualitatively using the idea of continuity of wave functions

Essential Idea:

- The microscopic quantum world offers a range of phenomena, the interpretation and explanation of which require new ideas and concepts not found in the classical world.

QUESTIONS?

Homework

#17-22