Engineering Physics

Course Code: BPHY101L; Course Type: Theory Only (TH)

Jitendra K. Behera (PhD)
Assistant Professor
jitendra.behera@vit.ac.in
Office: #121-E, PRP

Module-4

Application of Quantum Physics

Syllabus

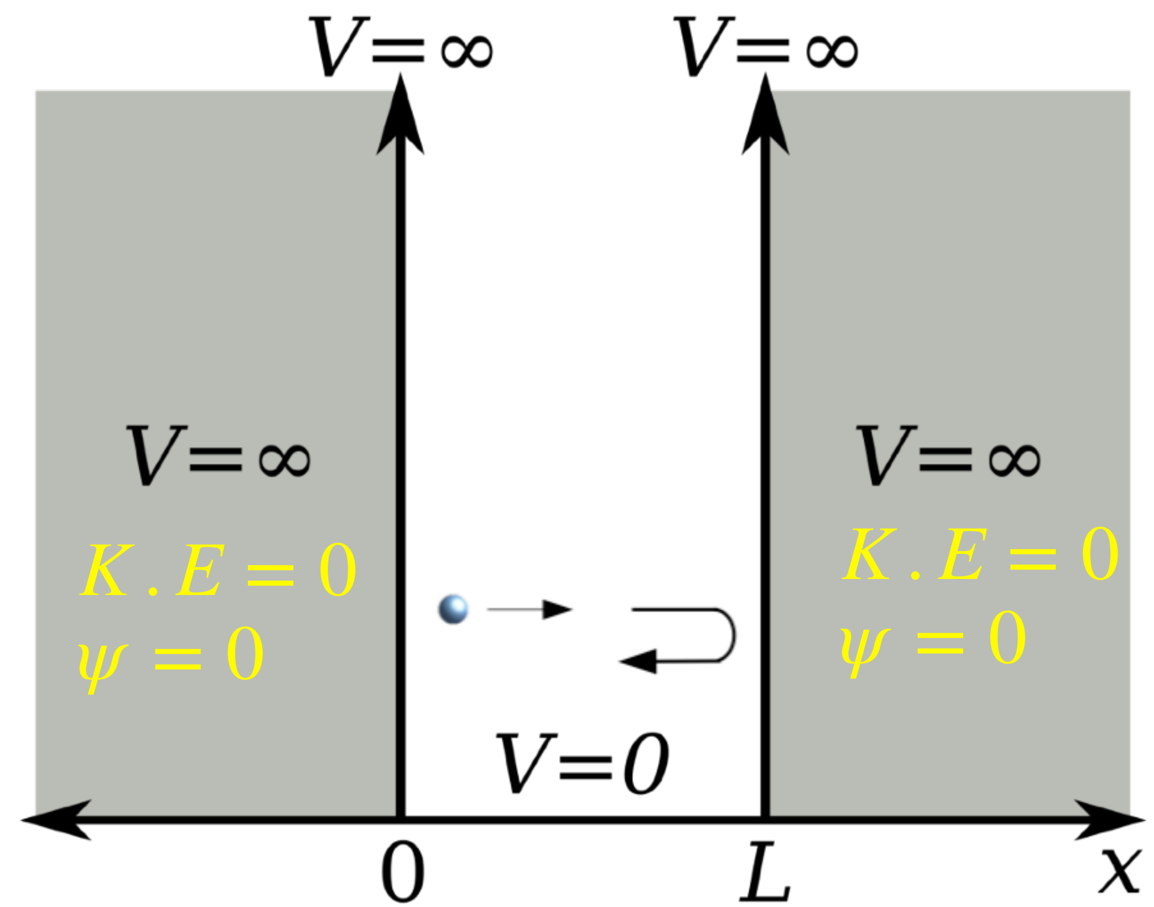
Eigenvalues and eigenfunction of a particle confined in a one-dimensional box - Basics of nanophysics - Quantum confinement and nanostructures - Tunnel effect (qualitative) and scanning tunneling microscope.

Reference Books:

1. H. D. Young and R. A. Freedman, University Physics with Modern Physics, 2020, 15th Edition, Pearson, USA., Section 41.1 to 41.3, Page No: 1360-1365
2. Concepts of Modern Physics; Sixth Edition; Arthur Beiser
3. Raymond A. Serway, Clement J. Mosses, Curt A. Moyer Modern Physics, 2010, 3rd Indian Edition Cengage learning.

Particle in a 1-Dimensional Potential Box

Lets consider a particle is trapped in a one dimensional infinite potential box of length L



Our aim is to understand the properties of the particle by using Schrödinger Wave Equation to describe its :

- **Energy**
- **Wavefunction**
- **Probability density**

As the potential is only position-dependent, so we can apply the time-independent Schrödinger Wave Equation, here, and we know that the equation is:

$$H\psi(x) = E\psi(x)$$

$$\Rightarrow \left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + V\right]\psi(x) = E\psi(x)$$

Boundary conditions

$$V(x) = \begin{cases} 0 & \text{if } 0 \leqslant x \leqslant L \\ \infty & \text{otherwise} \end{cases}$$

(i) at, $x = 0, \psi = 0$ **(ii) at,** $x = L, \psi = 0$

Particle in a 1-Dimensional Potential Box

Boundary conditions

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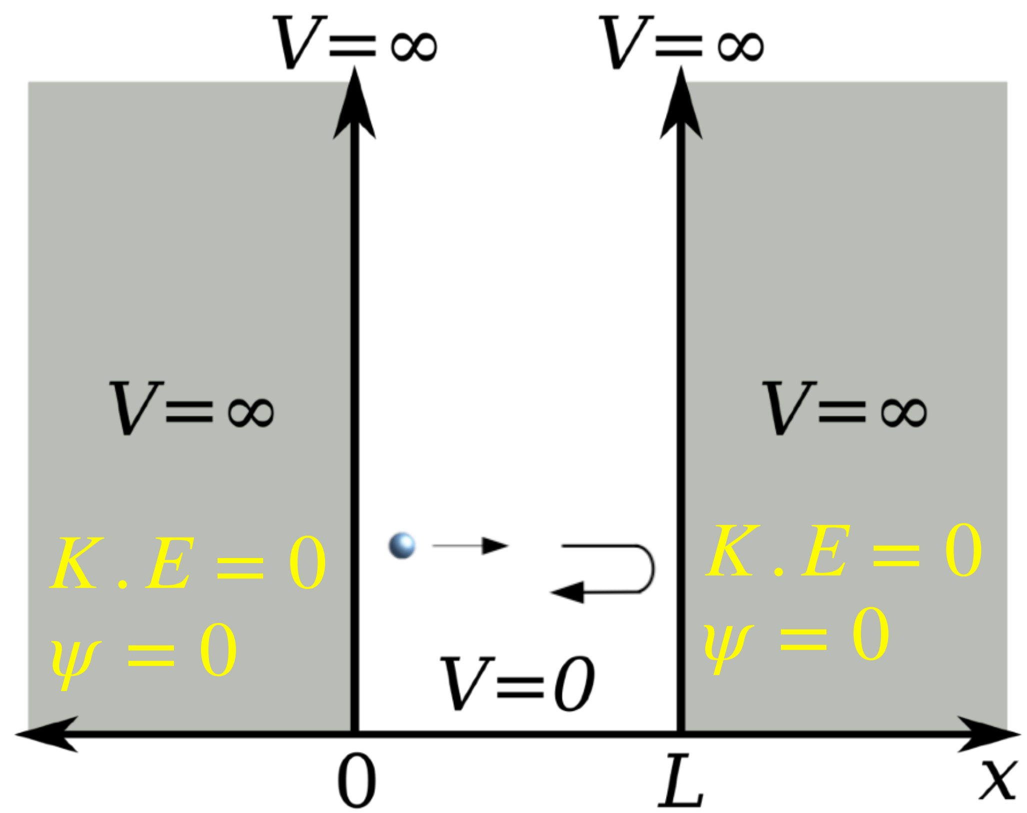


Three important steps

1. Solve time independent Schrodinger equation to get $\psi(x)$

2. Show that energy levels are quantized using boundary conditions

$$\psi(x=0) = \infty \quad \text{and} \quad \psi(x=L) = \infty$$

3. Find the complete wavefunctions using normalization $\int_0^L |\psi(x)|^2 dx = 1$

Particle in a 1-Dimensional Potential Box

$$\left[-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} + V\right]\psi(x) = E\psi(x)$$

$$\Rightarrow \frac{\partial^2\psi(x)}{\partial x^2} + \frac{2m}{\hbar^2}\left(E - V\right)\psi(x) = 0$$

For particle, $V(x) = 0$

$$\Rightarrow \frac{\partial^2\psi(x)}{\partial x^2} = -\frac{2mE}{\hbar^2}\psi(x)$$

$$\Rightarrow \frac{\partial^2\psi(x)}{\partial x^2} = -k^2\psi(x) \qquad \therefore k = \sqrt{\frac{2mE}{\hbar^2}}$$

$$\Rightarrow \frac{\partial^2\psi(x)}{\partial x^2} + k^2\psi(x) = 0$$

it is second order partial differential equation, and the possible solution for the equation is:

$$\psi(x) = A\sin(kx) + B\cos(kx)$$

where, A & B are constant

Boundary conditions:

- $V=\infty$ for $x \le 0$ and $x \ge L$
- $V=0$ for $0 < x < L$

(i) at, $x = 0, \psi = 0$ **(ii) at,** $x = L, \psi = 0$

2. Let's apply the Boundary conditions (i):

(i) at, $x = 0, \psi = 0$

$$\Rightarrow \psi = A\ sin(kx) + B\ cos(kx)$$

$$\Rightarrow \psi = 0 + B\ cos(0) \quad \Rightarrow \quad 0 = 0 + B$$

$$\Rightarrow B = 0$$

So the wave function reduced to:

$$\psi = A\ sin(kx)$$

Let's apply the Boundary conditions (ii):

(ii) at, $x = L, \psi = 0$

$$\Rightarrow \psi = A\ sin(kx) = A\ sin(kL) = 0$$

$$\Rightarrow kL = n\pi \ldots\ldots n = 1, 2, 3..$$

Particle in a 1-Dimensional Potential Box

so now we have:

$$\therefore k = \sqrt{\frac{2mE}{\hbar^2}} \qquad kL = n\pi$$

$$\Rightarrow \frac{n\pi}{L} = \sqrt{\frac{2mE}{\hbar^2}} \Rightarrow \frac{n^2\pi^2}{L^2} = \frac{2mE}{\hbar^2}$$

$$\Rightarrow \frac{n^2\pi^2\hbar^2}{2mL^2} = E \Rightarrow E = \frac{n^2\pi^2\hbar^2}{2mL^2}$$

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

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

We got energy of that trapped article, lets Let's find its wave function(i):

we know that: $\psi = A\ sin(kx)$ & $kL = n\pi$

3. Now apply the normalization to the wave function:

$$\Rightarrow \int_0^L \psi^* \psi \ dx = \int_0^L |\psi|^2 dx = 1$$

$$\Rightarrow \int_0^L \left(A \sin\left(\frac{n\pi x}{L}\right)\right)^2 dx = \int_0^L A^2 \sin^2\left(\frac{n\pi x}{L}\right) dx = 1$$

$$\Rightarrow \frac{A^2}{2} \int_0^L \left(1 - \cos 2(kx)\right) dx = 1$$

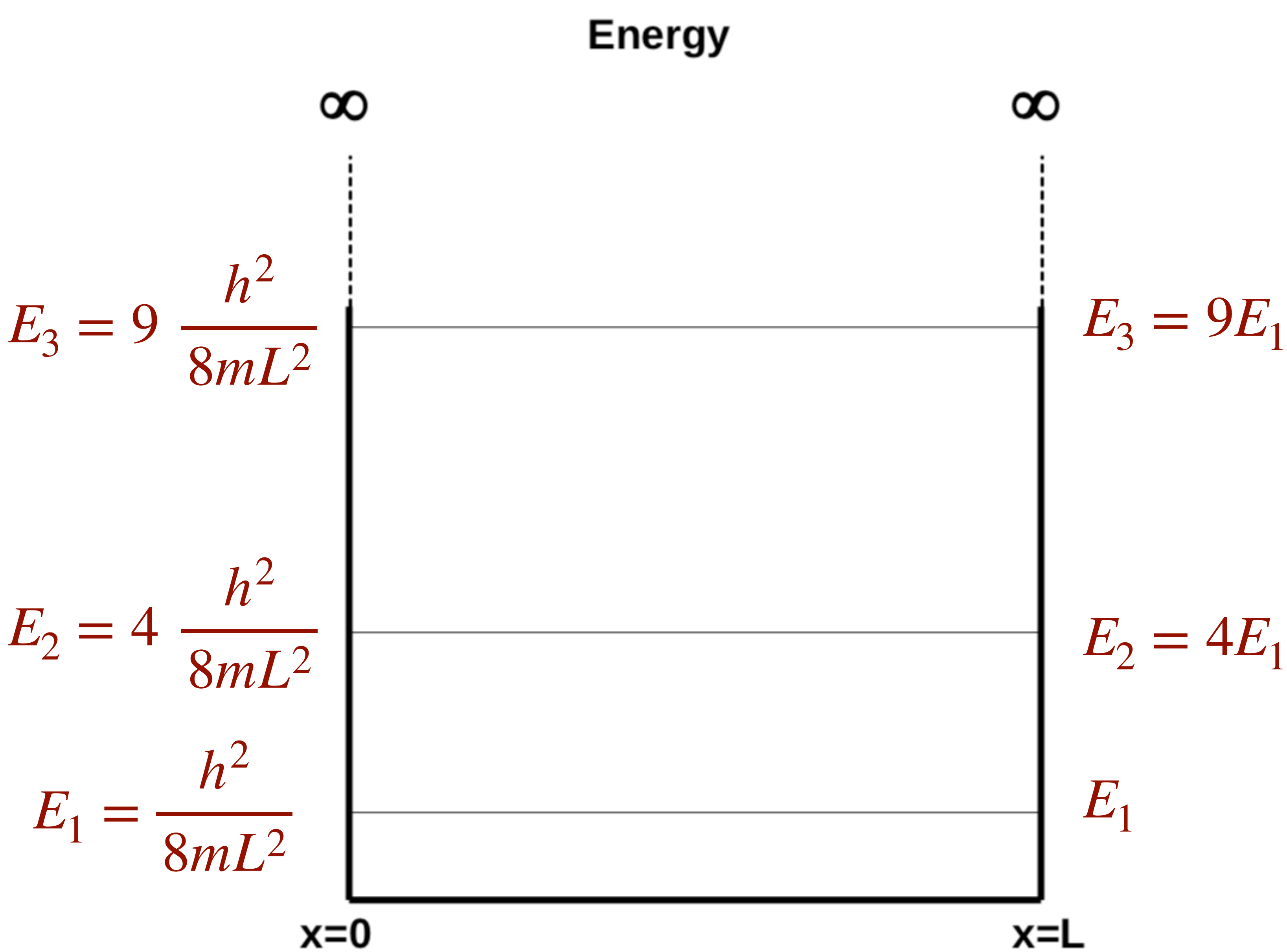
$$\Rightarrow \frac{A^2}{2} \left[[L]_L - [0]_0\right] = 1 \Rightarrow A = \sqrt{\frac{2}{L}}$$

$$\Rightarrow \psi = \sqrt{\frac{2}{L}}\ sin\left(\frac{n\pi x}{L}\right)$$

Particle in a 1-Dimensional Potential Box: Energy

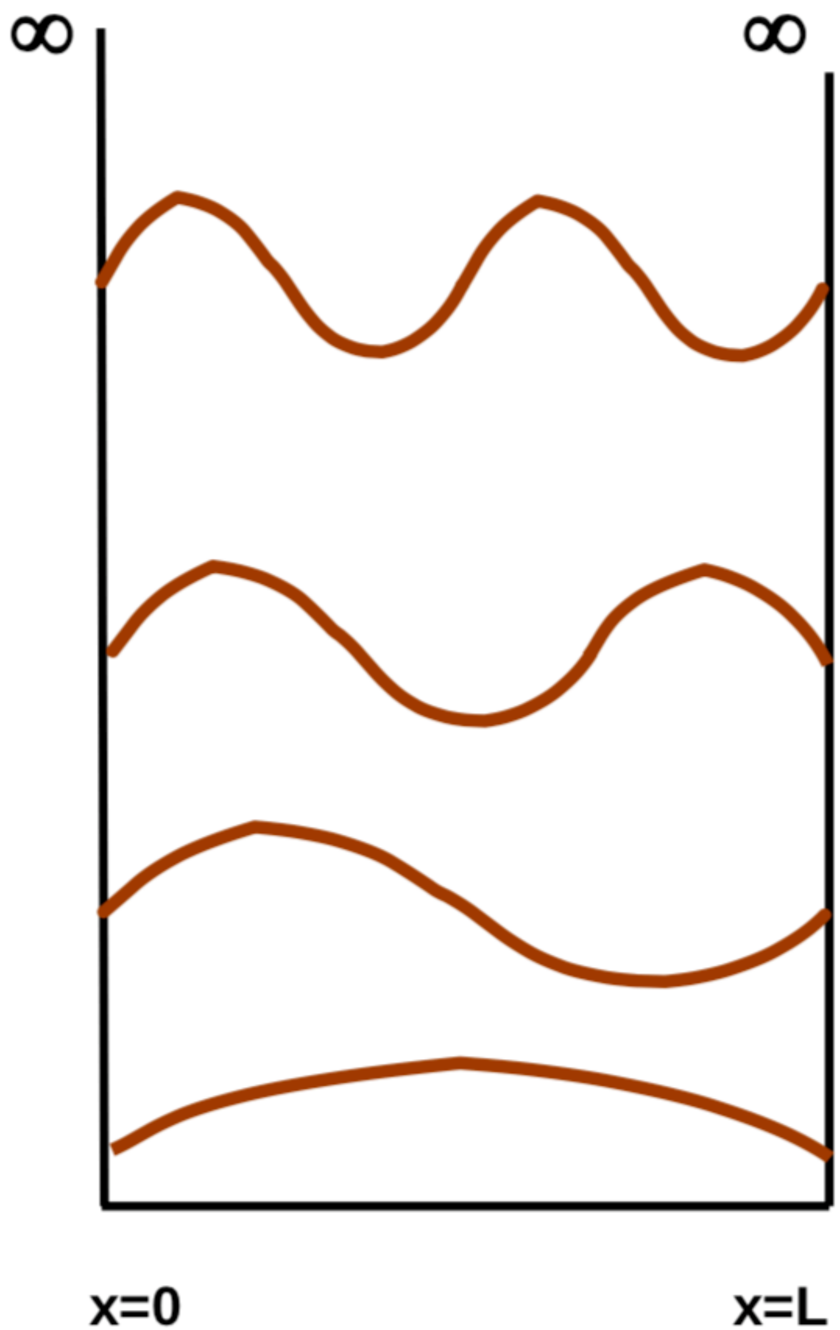
so now we have energy and the wave function as :

$$E_n = \frac{n^2h^2}{8mL^2} \qquad E_1 = \frac{h^2}{8mL^2} \qquad , E_2 = 4E_1,\ E_3 = 9E_1 \ldots .$$



Particle in a 1-Dimensional Potential Box: Wavefunction

so the wave function as : $\psi = \sqrt{\frac{2}{L}}\, sin(\frac{n\pi x}{L})$



n=4 $\psi_4(x) = \sqrt{\frac{2}{L}} \sin\left(\frac{4\pi}{L}x\right)$

n=3 $\psi_3(x) = \sqrt{\frac{2}{L}} \sin\left(\frac{3\pi}{L}x\right)$

n=2 $\psi_2(x) = \sqrt{\frac{2}{L}} \sin\left(\frac{2\pi}{L}x\right)$

n=1 $\psi_1(x) = \sqrt{\frac{2}{L}} \sin\left(\frac{\pi}{L}x\right)$

Particle in a 1-Dimensional Potential Box

so now we have energy and the wave function as :

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

$$\psi = \sqrt{\frac{2}{L}}\, sin(\frac{n\pi x}{L})$$

The probability density is defined as : $P = |\psi|^2$

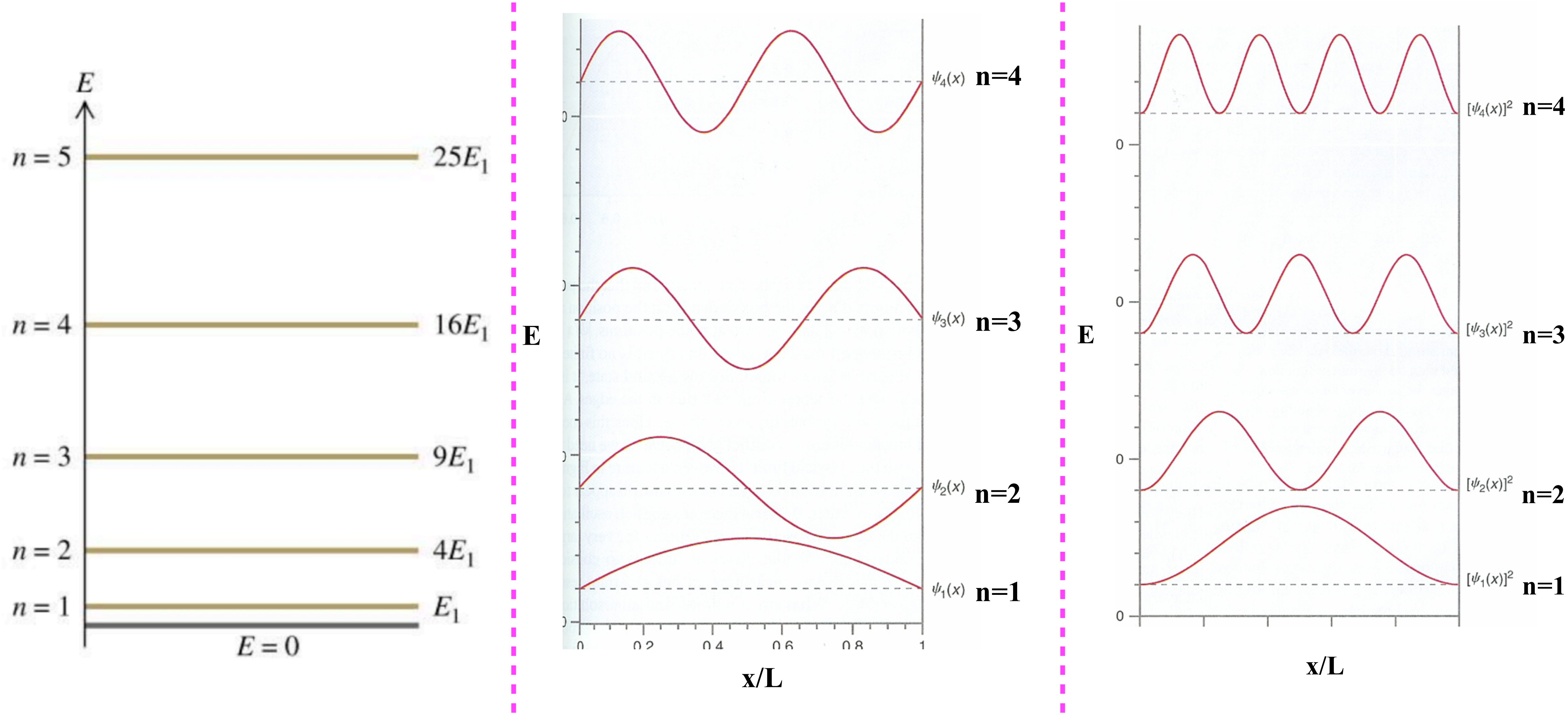
$$P = \frac{2}{L}\, sin^2(\frac{n\pi x}{L})$$

Graphical representation of E, ψ. and P

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

$$\psi = \sqrt{\frac{2}{L}}\, sin(\frac{n\pi x}{L})$$

$$P = \frac{2}{L}\, sin^2(\frac{n\pi x}{L})$$



$$E_1 : E_2 : E_3 \ldots : E_n = 1 : 4 : 9 ... : n^2$$

Particle in a 3-Dimensional Potential Box

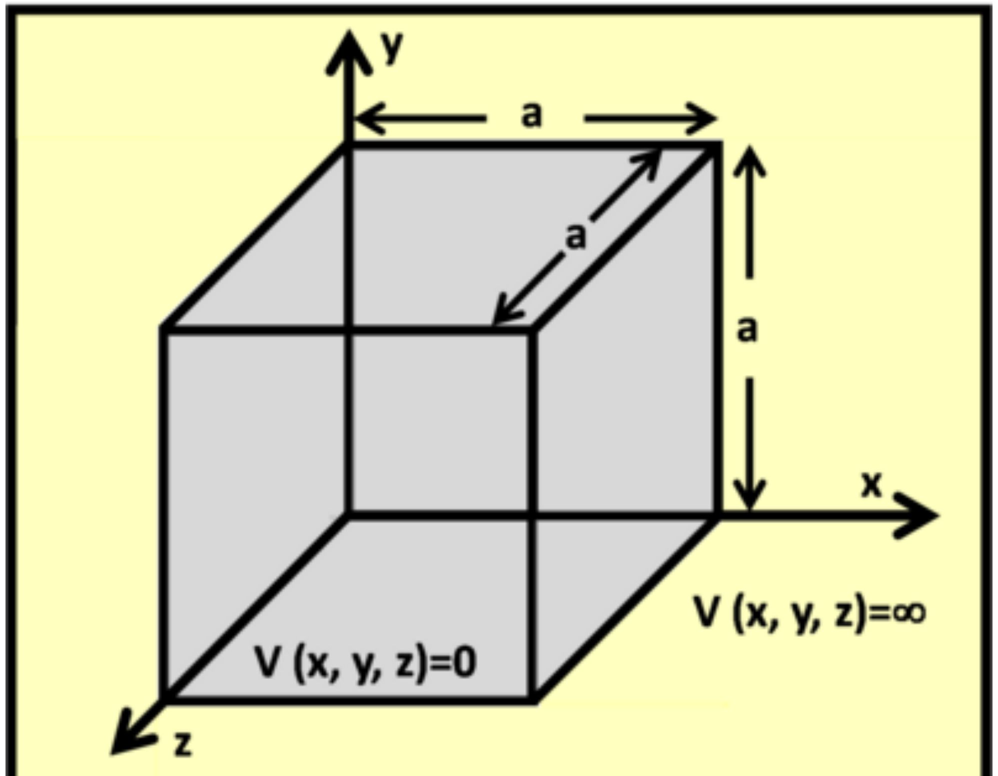


Fig. Particle in 3D Cubic Rigid Box

Wave functions and energies for particle in a 3D box:

$$\psi(x) = \sqrt{\frac{2}{a}}\,\sin\left(\frac{n_x \pi x}{a}\right) \qquad n_x = \{1,2,3,\ldots\}$$

$$\psi(y) = \sqrt{\frac{2}{b}}\,\sin\left(\frac{n_y \pi y}{b}\right) \qquad n_y = \{1,2,3,\ldots\}$$

$$\psi(z) = \sqrt{\frac{2}{c}}\,\sin\left(\frac{n_z \pi z}{c}\right) \qquad n_z = \{1,2,3,\ldots\}$$

eigenfunctions

$$E_x + E_y + E_z = E = \frac{\hbar^2 \pi^2}{2m}\left(\frac{n_x^2}{a^2} + \frac{n_y^2}{b^2} + \frac{n_z^2}{c^2}\right)$$

eigenvalues

$$E = \frac{\hbar^2 \pi^2}{2mL^2}\left(n_x^2 + n_y^2 + n_z^2\right)$$

eigenvalues if $a = b = c = L$

Facts Learn from Particle in a 1-D Potential Box

Sr.	Particular	Classical Mechanics	Quantum Mechanics
1	Energy of particle	A particle enclosed in a rigid box can have any value of energy from 0 to ∞	Only certain discrete values of energy that are integral multiples of $\frac{h^2}{8mL^2}$ are permitted
2	Minimum value of energy	Minimum energy of the particle can be zero.	Minimum energy of the particle cannot be zero.

- The energy of a particle is quantized. This means it can only take on discrete energy values.
- The lowest possible energy for a particle is NOT zero (even at 0 K).
- This means the particle always has some kinetic energy.
- The square of the wavefunction is related to the probability of finding the particle in a specific position for a given energy level.
- In classical physics, the probability of finding the particle is independent of the energy and the same at all points in the box

Particle in a 1-D Potential Box: Numerical

Calculate the ground state and third excited energies of an electron trapped in one dimensional potential well of width L=2 nm.

Mass of electron, m= 9.1 x 10^{-31}kg

Size of the box, L=2 nm= 2 x 10^{-9} m

Eigen-energies, $$E_n = \frac{n^2 \pi^2 \hbar^2}{2mL^2} = \frac{n^2 h^2}{8mL^2} = n^2 \frac{(6.63\times 10^{-34})^2}{8\times(9.1\times 10^{-31})\times(2\times 10^{-9})^2} \quad J$$

$$= n^2 \frac{43.9569\times 10^{-68}}{291.2\times 10^{-49}} \quad J \quad \approx n^2 0.151\times 10^{-19}\, J$$

$$= n^2 \frac{0.151\times 10^{-19}}{1.6\times 10^{-19}} eV = 0.0943\, n^2\, eV$$

For the ground state, n=1 and $E_1 = 0.0943\, eV$

For the third excited state, n=4 therefore, $E_4 = 16\, E_1 = 1.5\, eV$

Particle in a 1-D Potential Box: Numerical

An object of mass 1mg is confined to move between two rigid walls separated by 1cm. Calculate the minimum speed of the object. If the speed of the object is 3cm/s, find the corresponding value of n.

Mass m=1mg = 10^{-3} g

Box size L = 1cm = 10^{-2} m

Lowest energy

$$E_1 = \frac{\pi^2 \hbar^2}{2mL^2} = \frac{h^2}{8mL^2} = \frac{(6.63\times10^{-34})^2}{8\times10^{-3}\times(10^{-2})^2} = 5.49\times10^{-61} \quad J$$

$$v_1 = \sqrt{2mE_1} = \sqrt{2\times10^{-3}\times(5.49\times10^{-61})} = 3.31\times10^{-32}\, ms^{-1}$$

Do the second part!

Possible Question in Exam

1. Show that the energy of an electron in an infinite potential well varied as the square of the natural numbers.

2. Solve the Schrodinger wave equation for the motion of a free particle with mass 'm' and in a one-dimensional infinite potential well of width 'L'.

3. Calculate the minimum energy required to an electron to transit from the third energy level to the 4th energy level, if it is trapped within a one-dimension well of length 1.0 nm?

4. Derive the Eigen energy level of an particle trapped in a potential box. Plot the Energy, corresponding wave function and probability of the electron if it is in the 3rd excited state.

5. A particle is confined to one dimensional potential well of width 2 nm. It is found that when energy of the particle is 230 eV its Eigen functions have five antinodes. Find the mass of the particle in the lowest energy level.

6. An electron is bound in one-dimensional infinite well of width 5 nm. Find the energy values at 2nd excited states

Particle in a finite Potential Box

$$-\frac{\hbar^2}{2m}\frac{\partial^2\psi(x)}{\partial x^2} + V\psi(x) = E\psi(x)$$

Region-1, $V \neq 0$

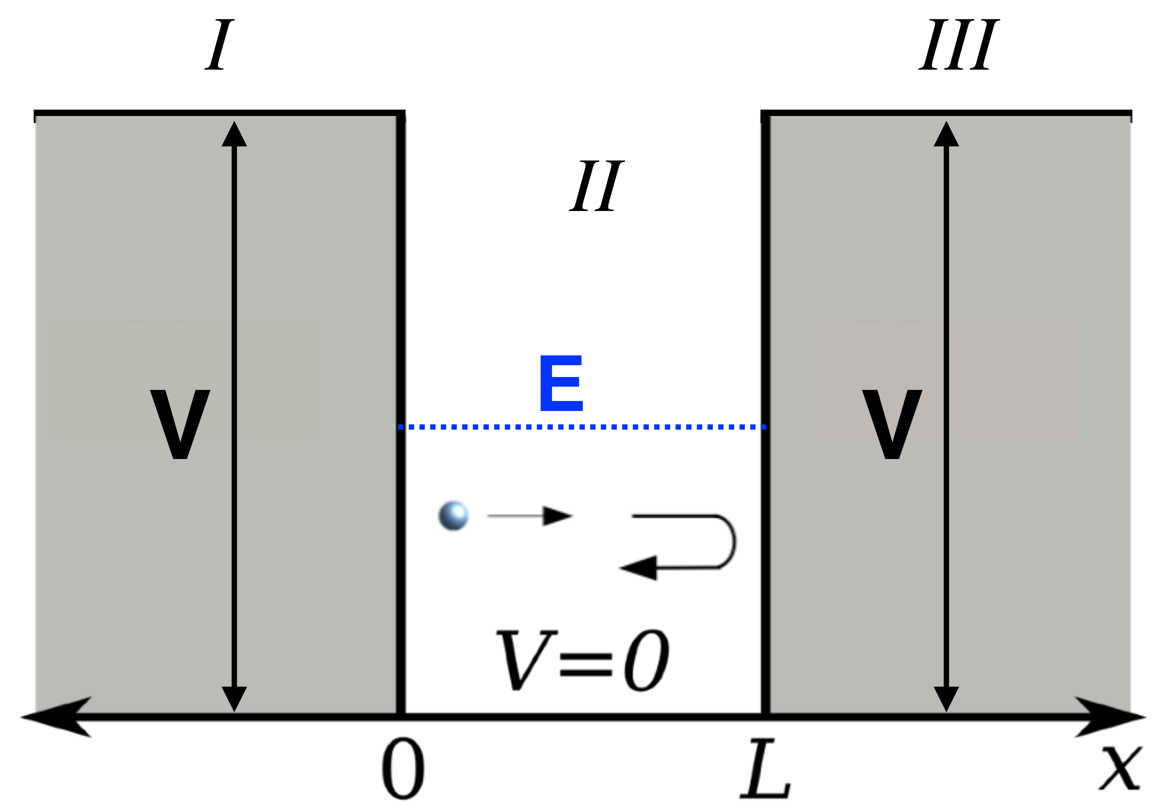
$$\Rightarrow \frac{\partial^2\psi(x)}{\partial x^2} + \frac{2m}{\hbar^2}(E - V)\ \psi(x) = 0$$

Region-2, $V = 0$

$$\Rightarrow \frac{\partial^2\psi(x)}{\partial x^2} + \frac{2mE}{\hbar^2}\ \psi(x) = 0$$

Region-2, $V = 0$

$$\Rightarrow \frac{\partial^2\psi(x)}{\partial x^2} + \frac{2m}{\hbar^2}(E - V)\ \psi(x) = 0$$



$$V(x) = \begin{cases} V & x \leq 0 \quad Region-I \\ 0 & x \leq 0 - to - x \geq L \quad Region-II \\ V & x \geq L \quad Region-III \end{cases}$$

$$\psi_1(x) = Ae^{k_1 x}$$

$$\psi_2(x) = Ce^{k_2 x} + De^{-k_2 x}$$

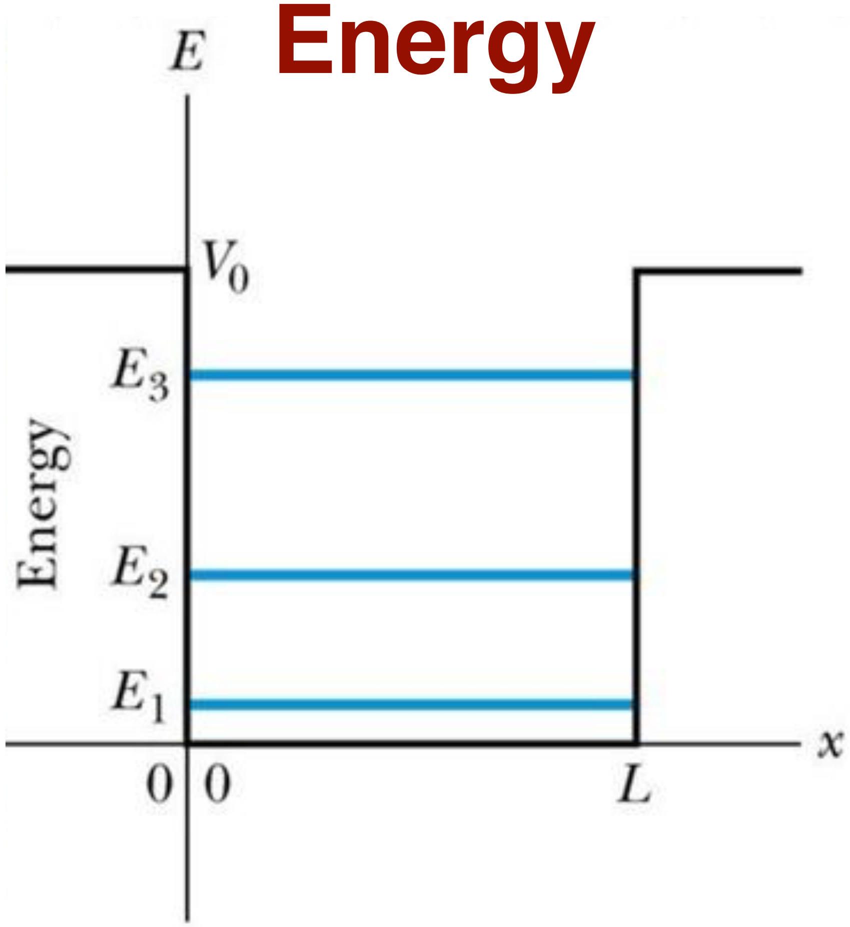
$$\psi_3(x) = Be^{-k_1 x}$$

$$\therefore k_1 = \sqrt{\frac{2m(V-E)}{\hbar^2}}$$

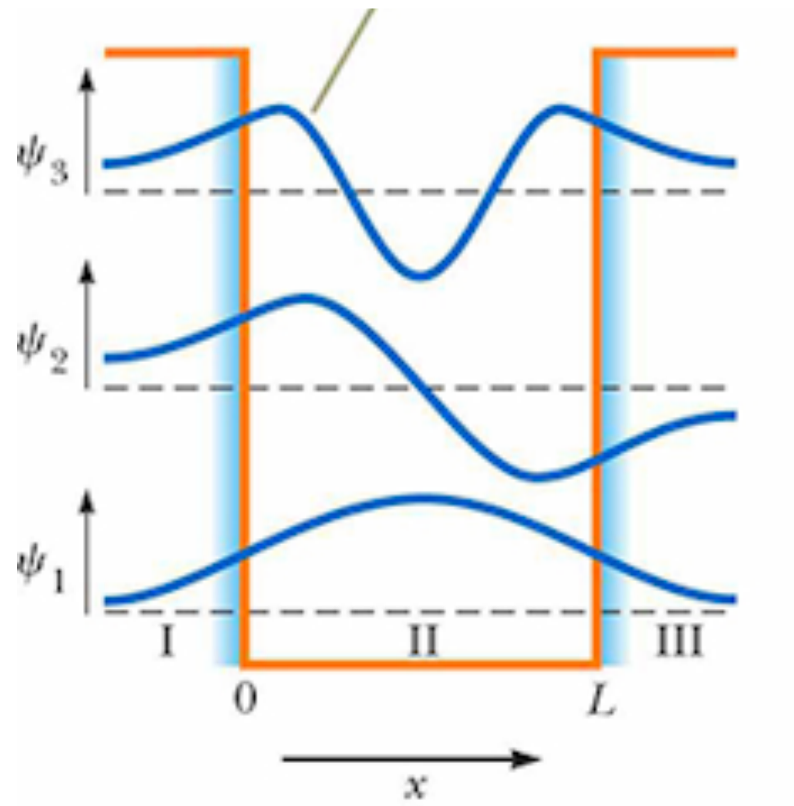
$$\therefore k_2 = \sqrt{\frac{2mE}{\hbar^2}}$$

Particle in a finite Potential Box

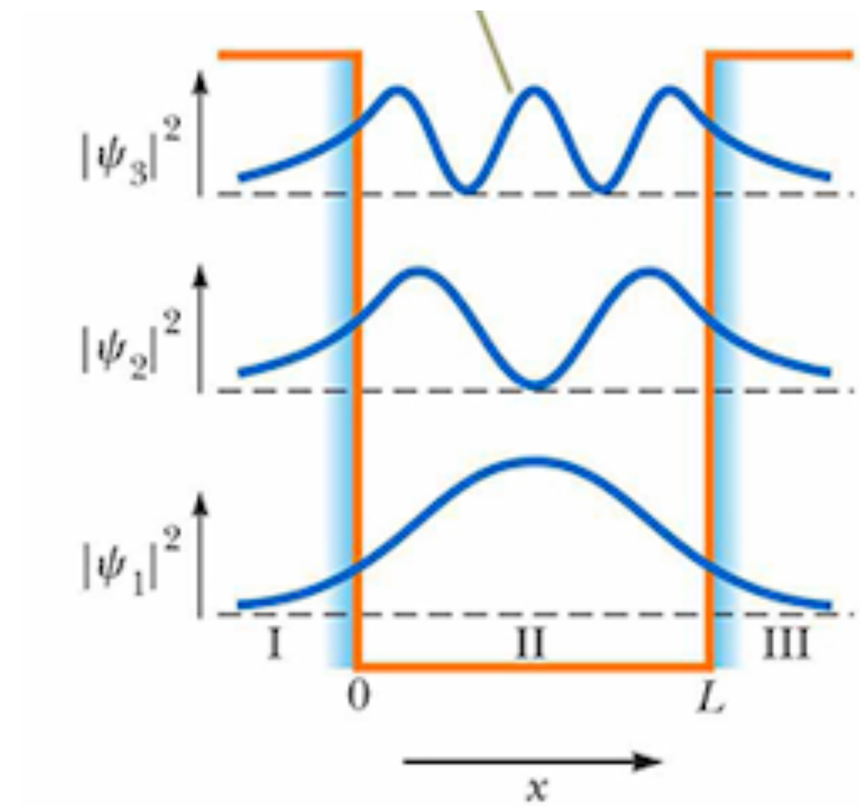
Energy



wave function



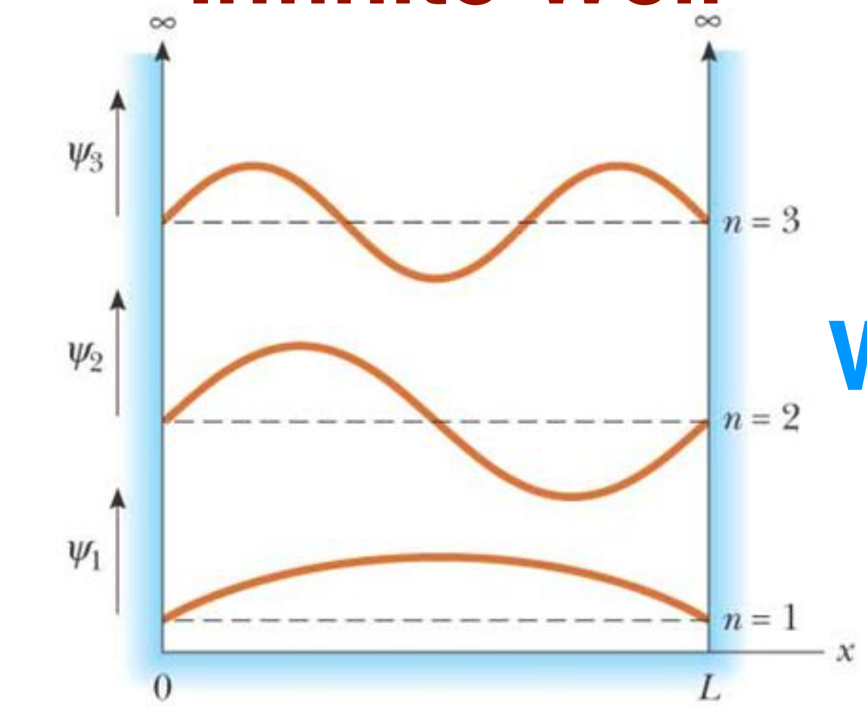
Probability



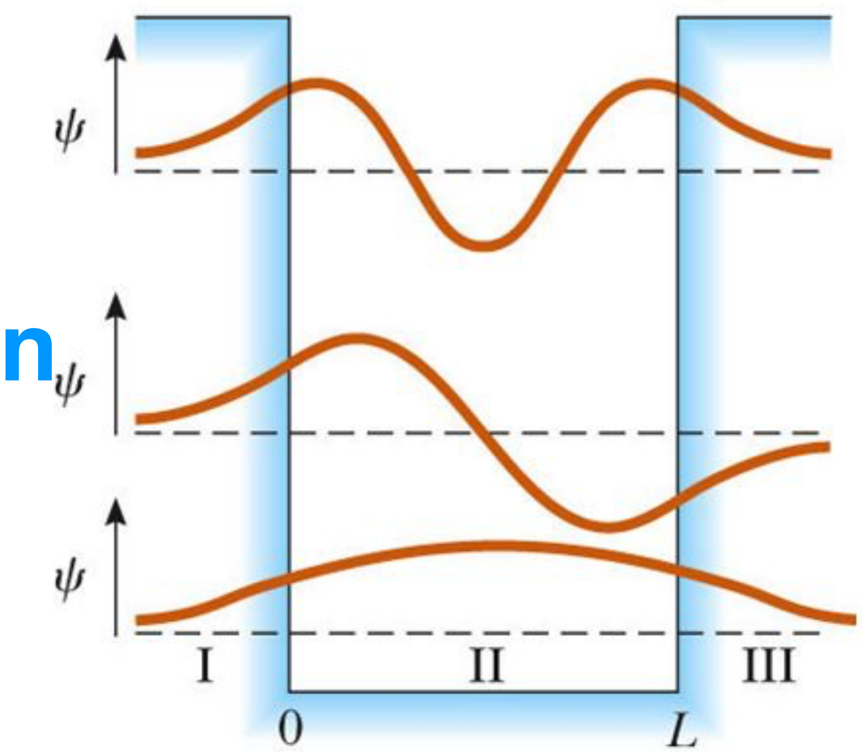
the wave function of the particle extends outside the well and the probability of the finding particle outside of the box increases

Infinite Vs Finite potential well

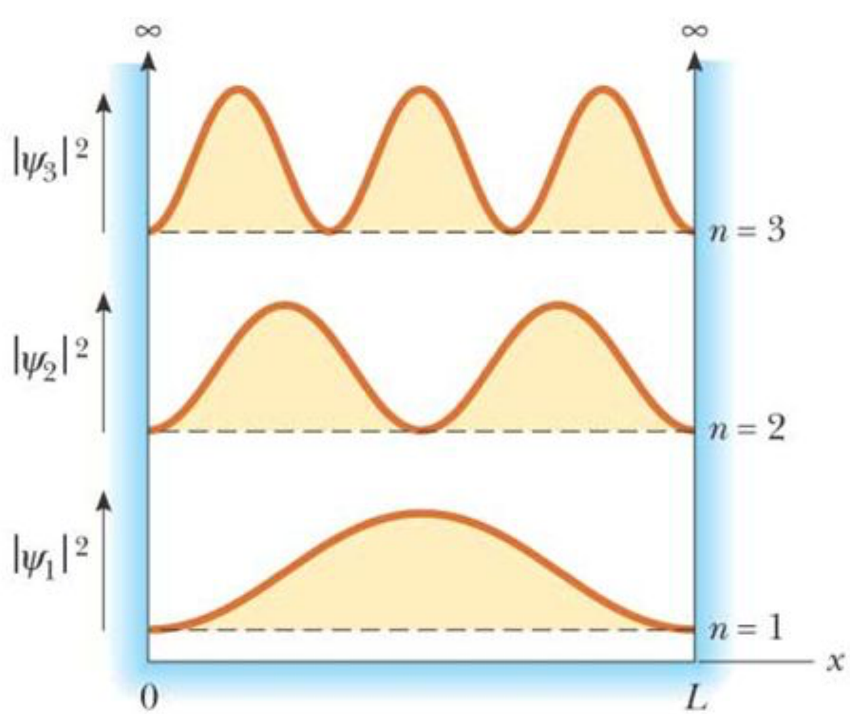
Infinite Well

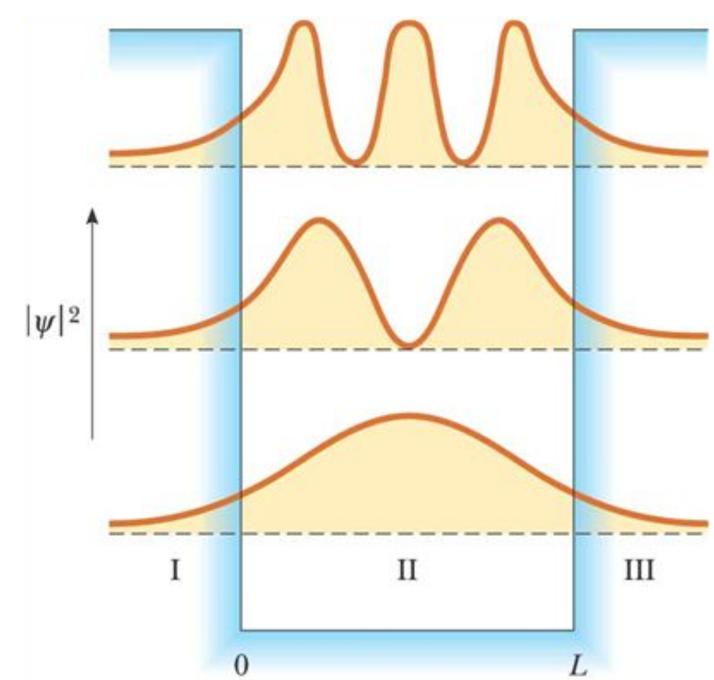


Finite Well



Wave function



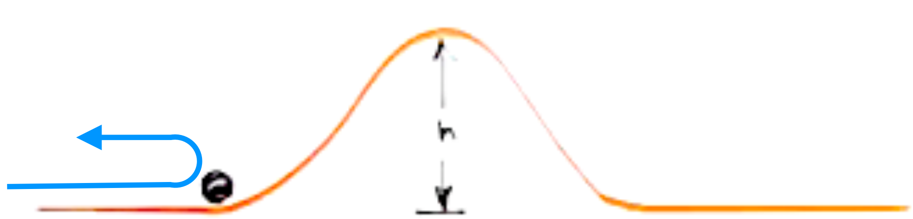


Probability

Tunneling

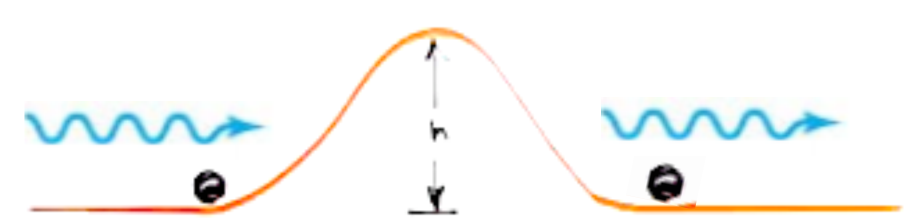
From our discussion of the finite potential well, the wave function of the particle **extends outside the well** and the probability of the finding particle outside of the box increases. So you can think that even if the **total energy, E of the particle is less than the V**, still, there is the probability we can find it outside, which is **forbidden in classical mechanics**. Here the concept of **tunneling** starts

Classical point of view



- **Macroscopic object**
- **The object having mass=m, K.E=E, PE=V=0**
- **if, E < V = mgh, it will not pass the Hill**

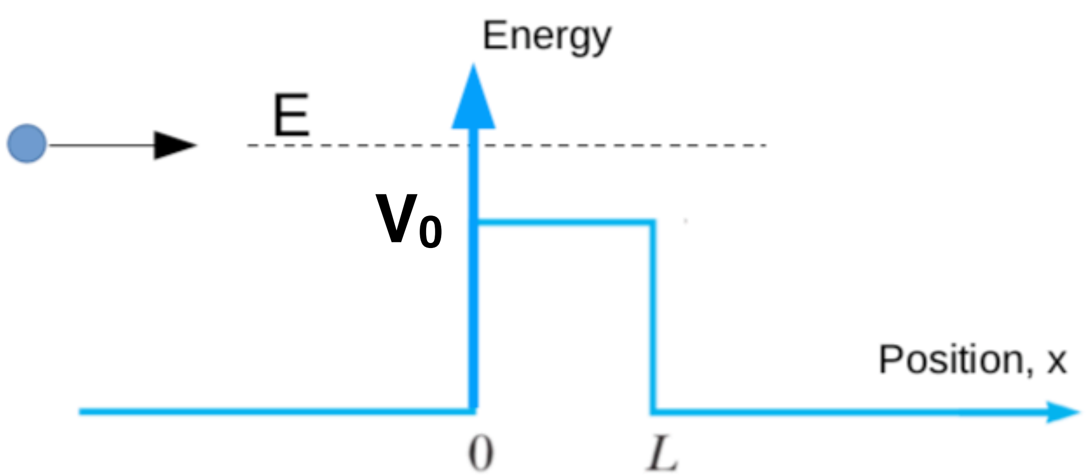
Quantum point of view



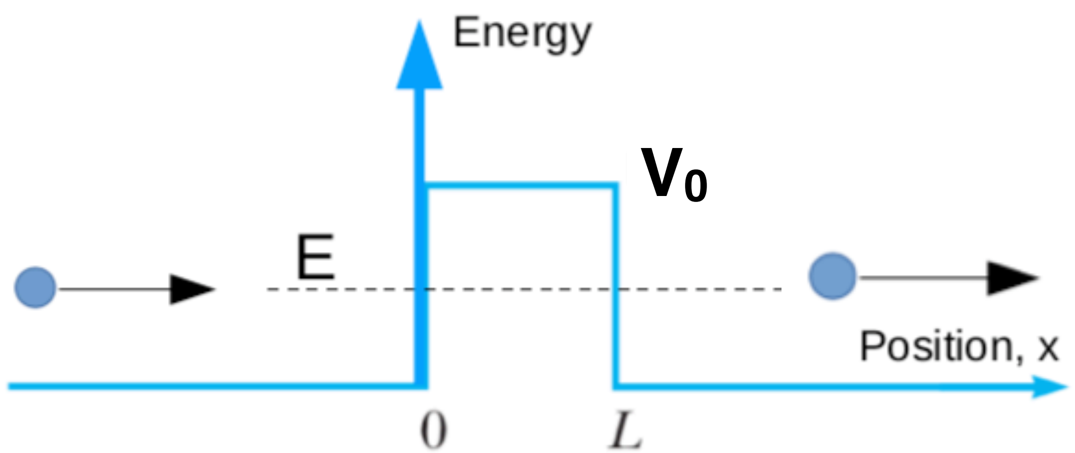
- **Microscopic object**
- **if, E<V, there is a finite probability the particle can found other side of the Hill**

Barriers and Quantum Tunneling

Consider a particle of energy ***E* approaching a potential barrier of height V_0** and the potential everywhere else is zero. Now we consider the situation where classically the particle does not have enough energy to surmount the potential barrier, $E < V_0$



(a) Particle crosses the barrier because **$E>V_0$**



(b) Particle does not cross the barrier because **$E<V_0$**

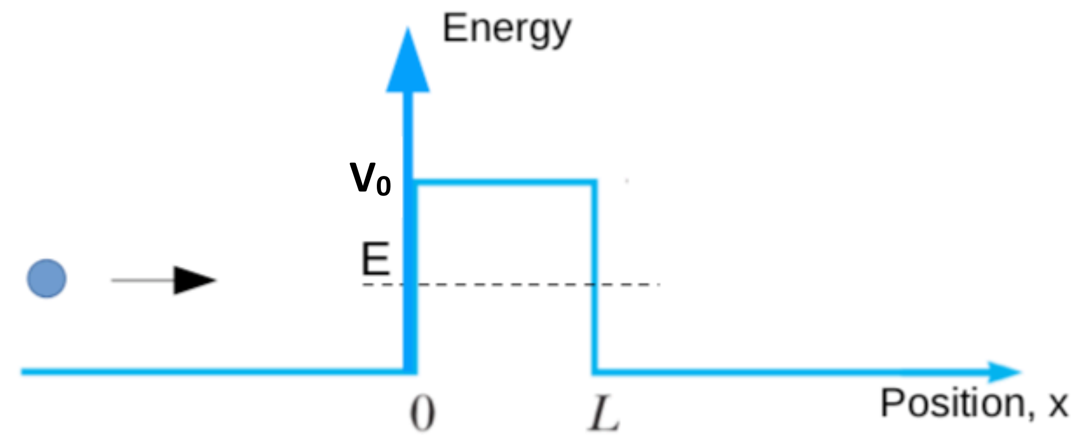
Quntum tunneling is a phenomenon in which an microscopic **object** such as an electron or atom **passes through a potential energy barrier** although that does not have sufficient energy to penetrate it.

Quantum Tunneling

Tunneling is purely a **quantum phenomena** and can understood by solving Schrodinger equation for a particle moving towards a potential barrier.

Time independent Schrodinger Equation is

$$\frac{-\hbar^2}{2m}\frac{d^2\psi}{x^2} + V_0(x)\psi = E\psi$$



Where the potential is

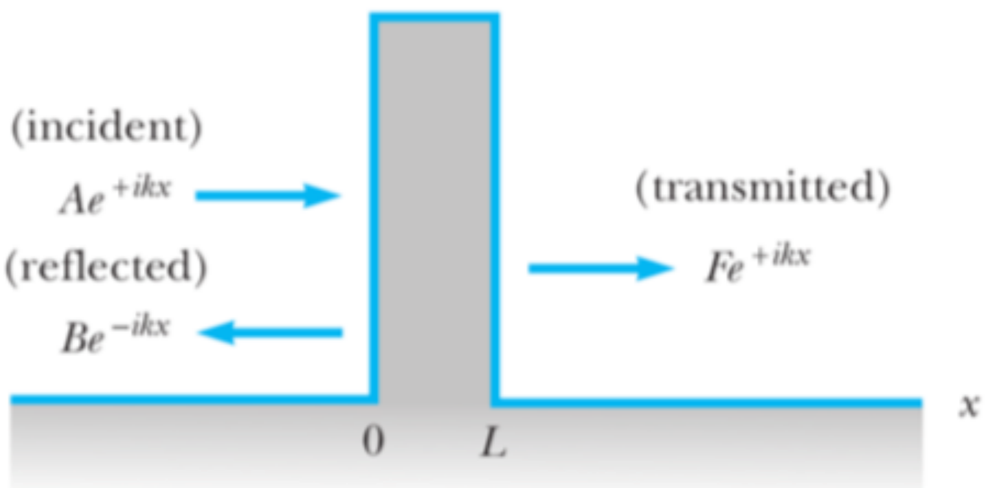
$$V_0(x) = \begin{cases} 0 & \text{if} \quad x < 0 \\ V_0 & \text{if} \quad 0 \leqslant x \leqslant L \\ 0 & \text{if} \quad x > L \end{cases}$$

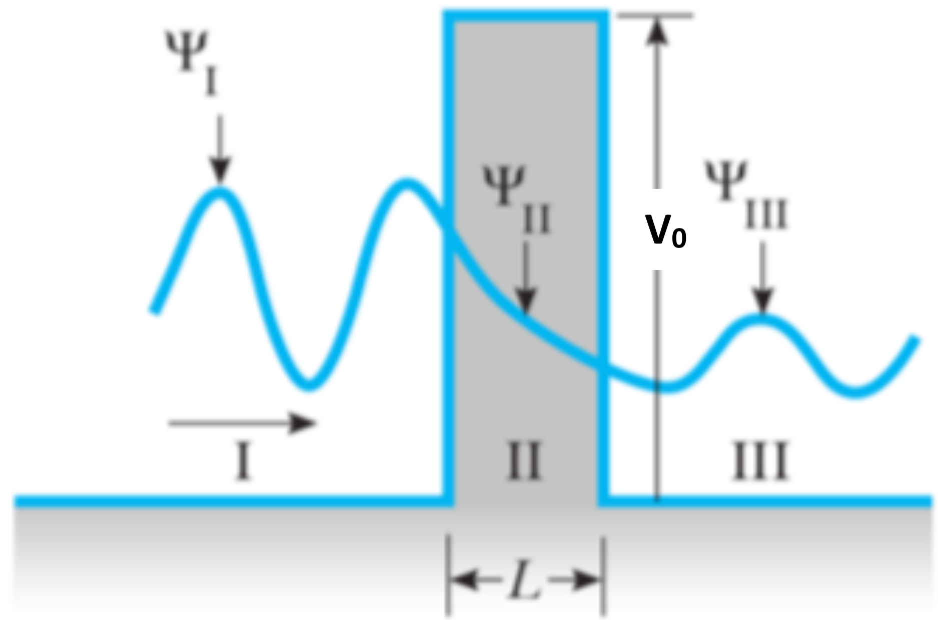
Quantum Tunneling

So quantum results that there is a non-zero probability

➔ the particle can penetrate the barrier and emerge on the other side

➔ **the incident particle can tunnel the barrier**





$\psi_1 =$ *Sinusoidal*

$\psi_2 =$ *Exponetntial Decay or Evanescent wave*

$\psi_3 =$ *Sinusoidal (lower amplitude)*

Reflection probability

$$R = \frac{(\Psi^*\Psi)_{\text{reflected}}}{(\Psi^*\Psi)_{\text{incident}}} = \frac{B^*B}{A^*A} = \frac{|B|^2}{|A|^2}$$

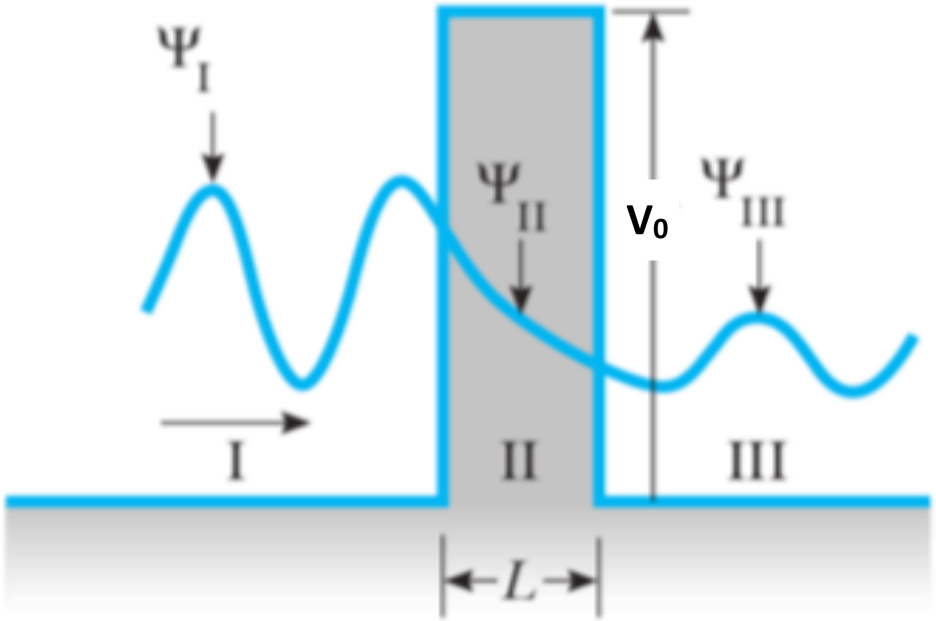
Transmission probability

$$T = \frac{(\Psi^*\Psi)_{\text{transmitted}}}{(\Psi^*\Psi)_{\text{incident}}} = \frac{F^*F}{A^*A} = \frac{|F|^2}{|A|^2}$$

$$R + T = 1$$

Remember, transmission probability is zero in classical physics!

Barriers and Tunneling



Region I ($x < 0$)	$V = 0$	$\frac{d^2\psi_1}{dx^2} + \frac{2m}{\hbar^2}E\psi_1 = 0$
Region II ($0 < x < L$)	$V = V_0$	$\frac{d^2\psi_{II}}{dx^2} + \frac{2m}{\hbar^2}(E - V_0)\psi_{II} = 0$
Region III ($x > L$)	$V = 0$	$\frac{d^2\psi_{III}}{dx^2} + \frac{2m}{\hbar^2}E\psi_{III} = 0$

The wave function in region II becomes:

$$\psi_{II} = Ce^{\kappa x} + De^{-\kappa x} \quad \text{where} \quad \kappa = \frac{\sqrt{2m(V_0 - E)}}{\hbar}$$

The transmission probability that describes the phenomenon of **tunneling** is:

$$T = \left[1 + \frac{V_0^2 \sinh^2(\kappa L)}{4E(V_0 - E)}\right]^{-1}$$

$$T = \left[1 + \frac{V_0^2 \sinh^2(\kappa L)}{4E(V_0 - E)}\right]^{-1} \xrightarrow{\sinh(kL) \xrightarrow{kL \to \infty} \frac{1}{2}e^{kL}} \boxed{T = 16\frac{E}{V_0}\left(1 - \frac{E}{V_0}\right)e^{-2\kappa L}}$$

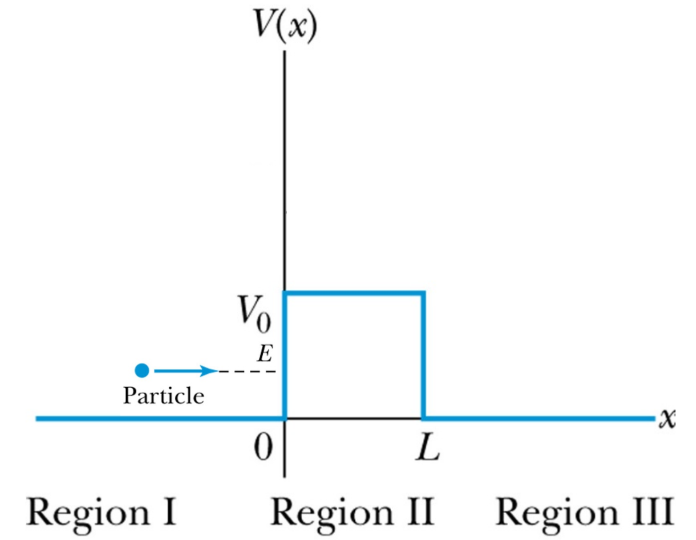
Tunneling: Problem

In a particular semiconducting device, electrons that are accelerated through a potential difference of 5 V attempt to tunnel through a barrier of width 0.8 nm and height 10 V. **What fraction of electrons are able to tunnel through the barrier?**

Given:

$$L = 0.8 \text{ nm}, E = 5\ eV, V_0 = 10\ V$$

$$T = 16\frac{E}{V_0}\left(1 - \frac{E}{V_0}\right)e^{-2\kappa L}$$



$$\kappa = \frac{\sqrt{2m(V_0 - E)}}{\hbar} = \frac{2\pi\sqrt{2mc^2(V_0 - E)}}{hc} = \frac{2\pi\sqrt{2\left(0.511\times10^6 eV\right)(10eV - 5eV)}}{1240 eV\cdot nm} = 11.5\ nm^{-1}$$

$$\therefore \kappa L = \left(11.5\ nm^{-1}\right)0.8\ nm = 9.2$$

$$T = \left[1 + \frac{V_0^2\sinh^2(\kappa L)}{4E(V_0 - E)}\right]^{-1} = \left[\frac{1 + (10eV)^2\sinh^2(9.2)}{4(5eV)(5eV)}\right]^{-1} = 4.1\times10^{-8}$$

Approximately → $T = 16\frac{E}{V_0}\left(1 - \frac{E}{V_0}\right)e^{-2\kappa L} = 16\left(\frac{5eV}{10eV}\right)\left(1 - \frac{5eV}{10eV}\right)e^{-2(9.2)} = 4.1\times10^{-8}$

Tunneling Applications

- $\alpha - \beta$, Radio Active decay
- Nuclear Fusion and Fission Process
- Tunnel Diode
- SQUID
- Quantum Computing
- **Scanning Tunnelling Microscope**

Quantum Tunneling Applications

- $\alpha - \beta$, Radio Active decay
- Nuclear Fusion and Fission Process
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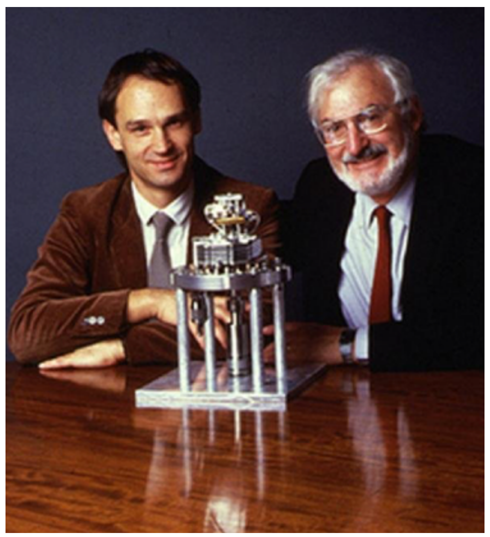
- SQUID
- Quantum Computing
- **Scanning Tunnelling Microscope**

Scanning Tunnelling Microscope (STM)

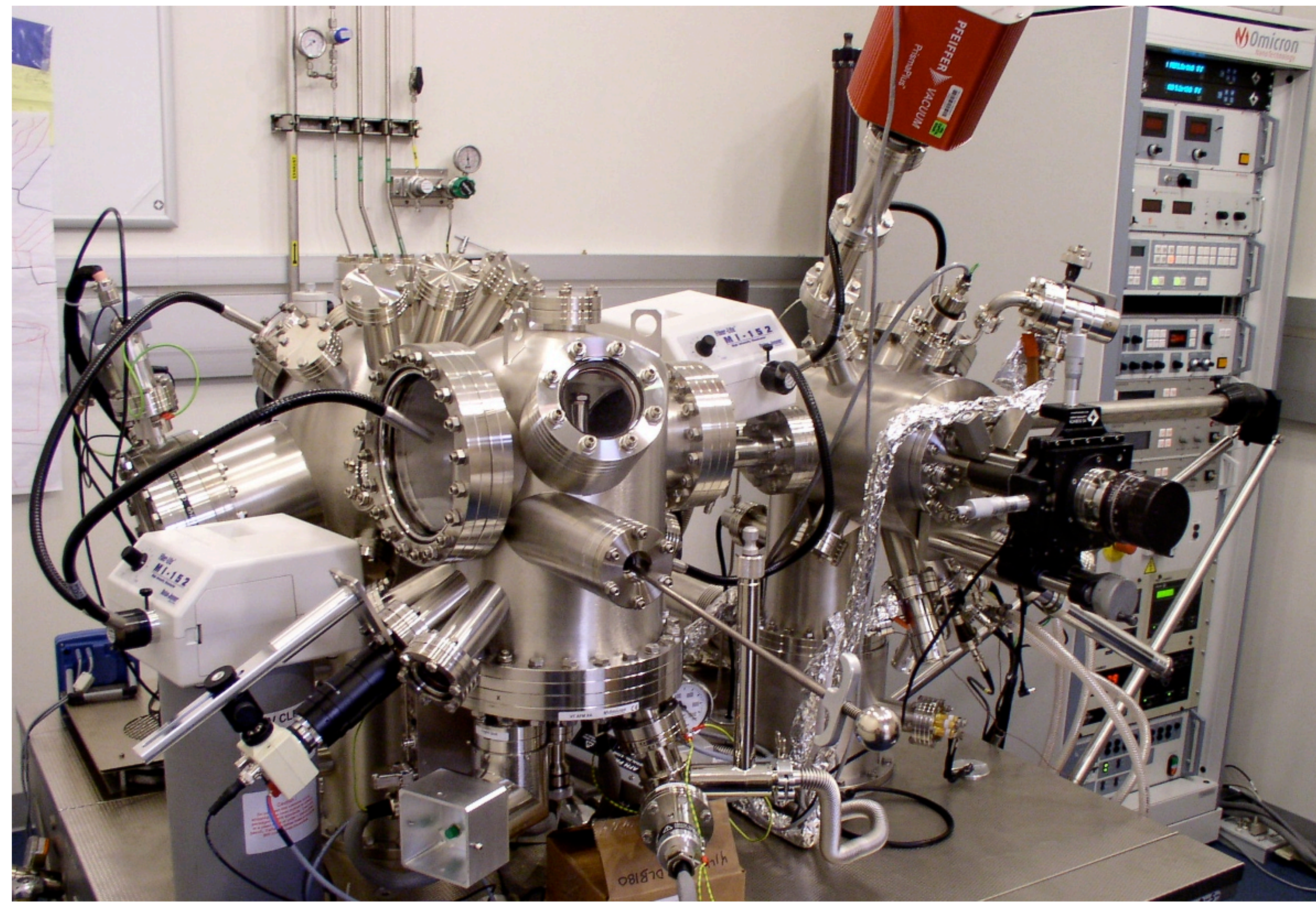
Scanning Tunneling Microscopy (STM), is an imaging technique used to obtain ultra-high resolution images at the atomic scale, **without using light or electron** beam **by using** the concept of **quantum tunneling**.



1981
Gerd Binnig and
Heinrich Rohrer
@ IBM Zürich

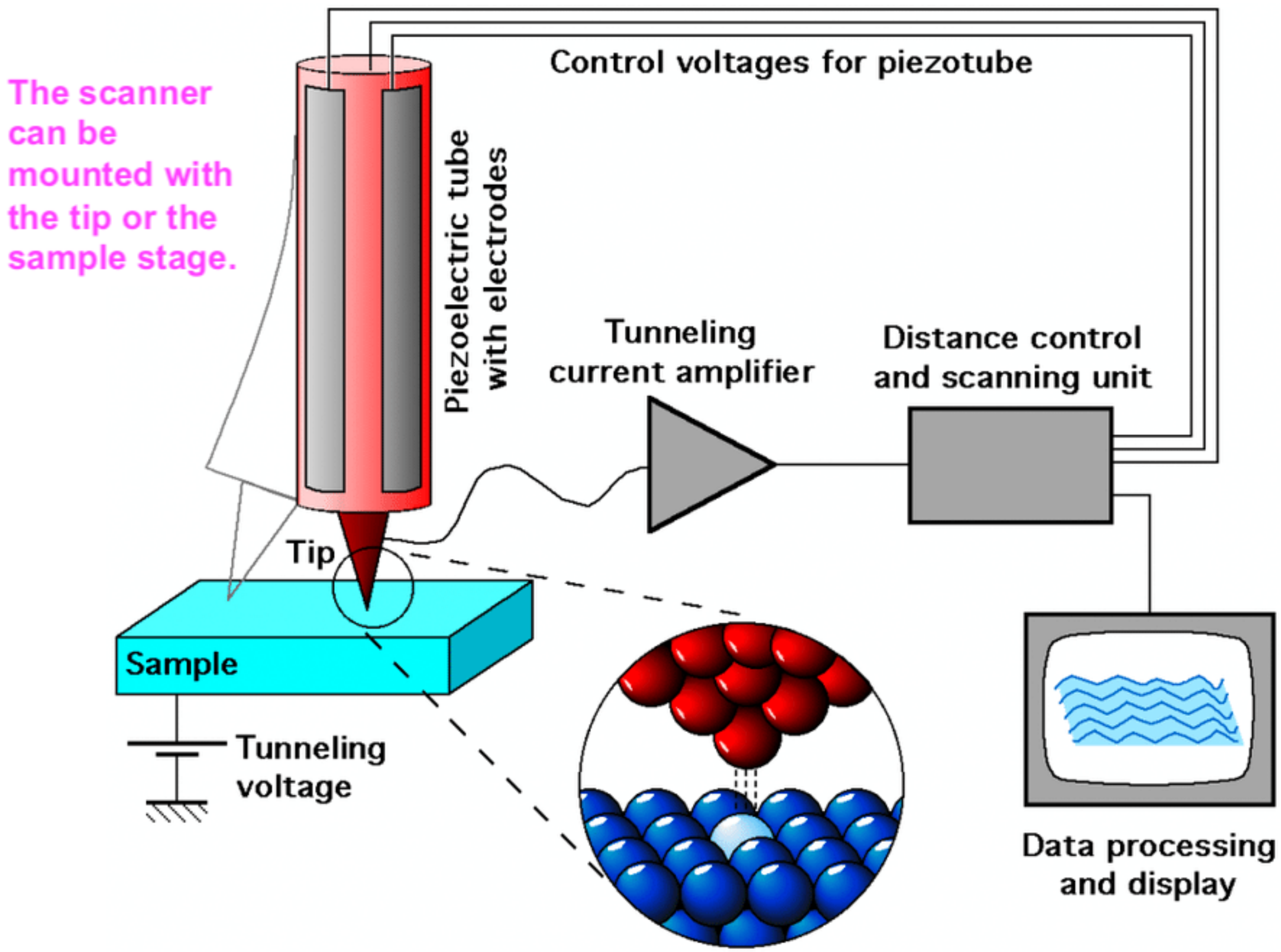
Nobel Prize in Physics in 1986

- Construction
- Working Principle
- Mode of Operation
- Applications



Ultra-high vacuum and low-temperature STM set-up. The system needs a clean environment such as the particle take 40 km distance travel for a single collision

STM: Construction



<u>Five basic components:</u>

1. Metal tip,
2. Piezoelectric scanner,
3. Current amplifier (nA),
4. Bipotentiostat (bias),
5. Feedback loop (current).

- Tunneling current from tip to sample or vice-versa depending on bias;
- Current is exponentially dependent on distance;
- Raster scanning gives 2D image;
- Feedback is normally based on constant current, thus measuring the height on surface.

STM: Construction

1. Metal tip: It is required to permits electrons to tunnel between tip and the sample. The metal should be good so that electrons motion is not hindered.

2. Piezoelectric scanner: It is need for fine tuning of the height. Peizoelectric material can change their length depending on the applied voltage. This property of the peizoelectric material is sued in STM.

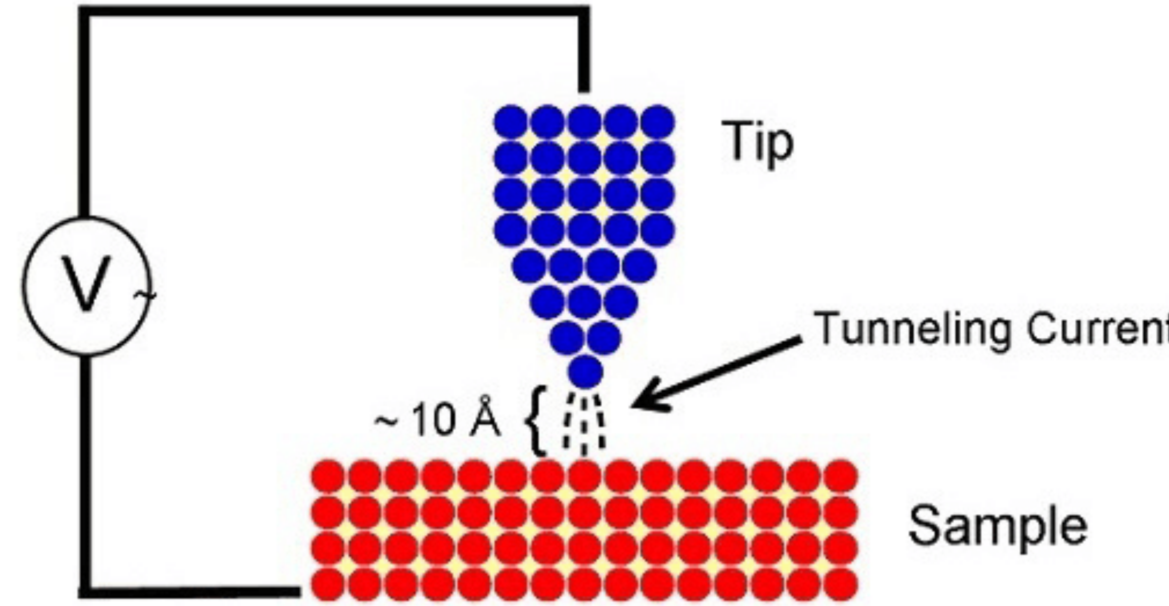
3. Current amplifier: The tunneling current we get is in the sub-nanoampere range. This has to be amplified for proper detection. Therefore a current amplifier is used.

4. Battery to apply bias voltage: A batter is used to apply voltage between sample and the metalic tip. The metalic tip is connected to cathode (-ve terminal) for permitting electrons to tunnel from the tip and sample is connected to anode.

5. Feedback loop: This is used in constant current mode. Using the feedback loop the height ia adjusted so that constant tunneling current flows.

STM: Working Principle

- STM is based on the concept of **quantum tunneling**
- An electrically conducting probe with a very sharp edge is brought near the surface to be studied
- The empty space between the tip and the surface represents the "barrier"
- The tip and the surface are two walls of the "potential well" electrons to tunnel through the vacuum separating the tip and the sample



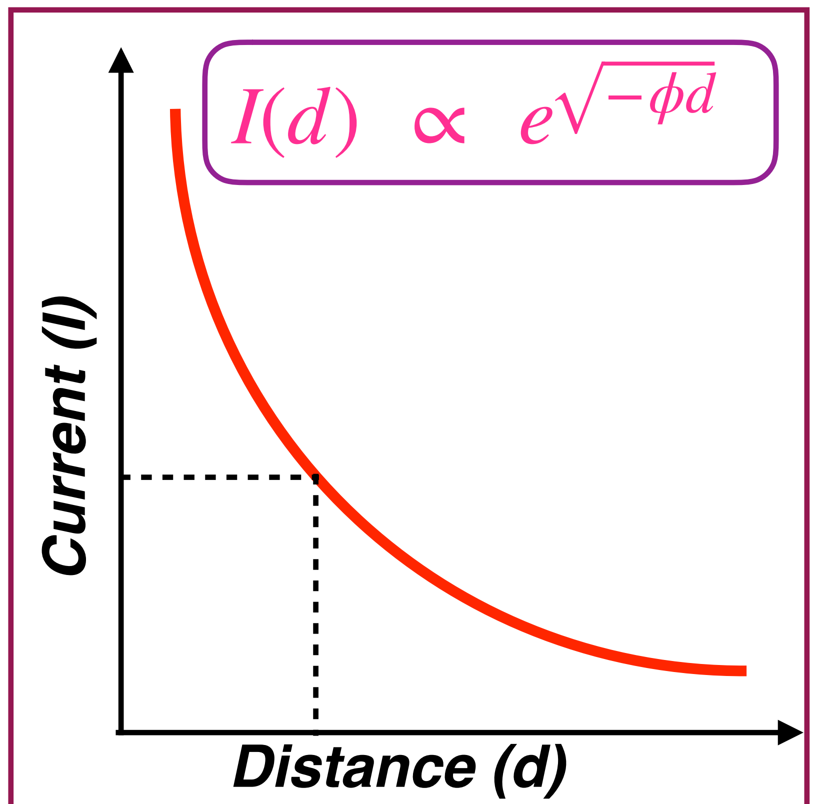
From the concept of tunneling from a potential barrier, we know that:

$$T = 16\frac{E}{V_0}\left(1-\frac{E}{V_0}\right)e^{-2\kappa L}$$

Tunneling current: $I \propto e^{-kd}$

$$\therefore k = \sqrt{\frac{2m\phi}{\hbar^2}}$$

ϕ: the work function (energy barrier)



- 0.1 nm change in separation produces n order of magnitude change in current
- Atomic scale resolution up to 0.1 nm
- Scan on the surface to give the 2D image of sample

STM: Working Principle

The **tip is brought close to the sample**.

A **bias voltage is applied** between the sample and the tip.

Fine control of the tip position is achieved by **piezoelectric scanner** tubes whose length can be altered by a control voltage. The scanner is gradually elongated until the **tip starts receiving the tunneling current**.

The **tip–sample separation** is then kept somewhere in the **4–7 A° range.**

Once tunneling is established, the sample **bias and tip position with respect to the sample are varied according to the requirements** of the experiment.

STM: Working Principle

As the number of electrons that will actually tunnel is vary dependent upon the thickness of the barrier, the **tunneling current depends on the sample-tip separation.**

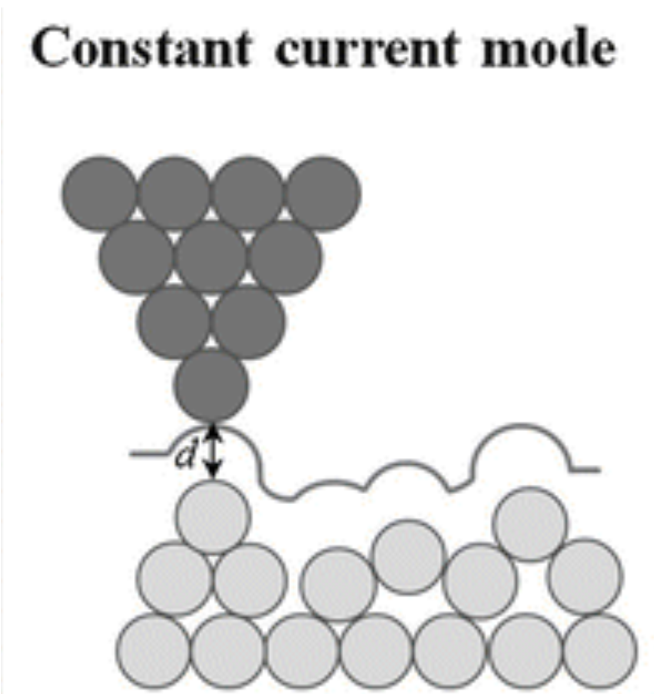
As the tip is moved across the surface, **the changes in surface height cause changes in the tunneling current.** Noting the tunneling current, surface height is estimated.

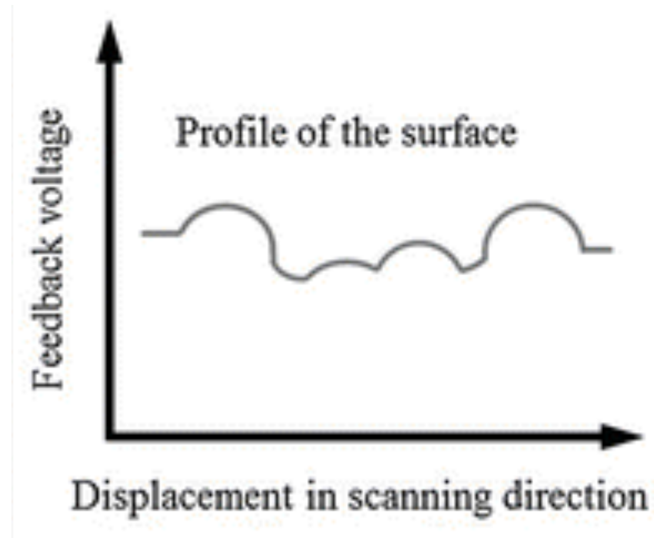
Digital images of the surface are formed in one of the two different modes:

(i) Constant-height mode: in this mode changes of the tunneling current are mapped directly.

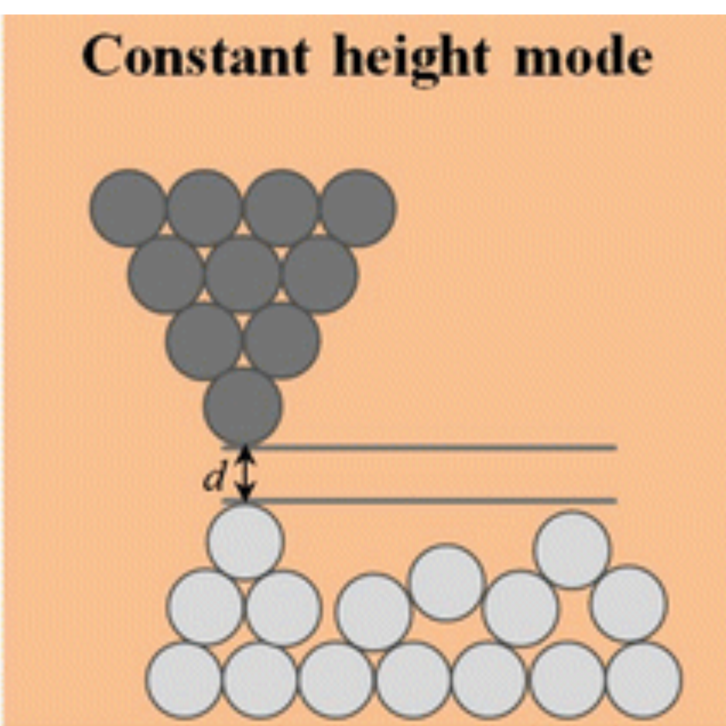
(ii) Constant-current mode: in this mode, the voltage that controls the height of the tip is recorded while the tunneling current is kept at a predetermined level. A feedback electronics adjust the height by a voltage to the piezoelectric height-control mechanism.

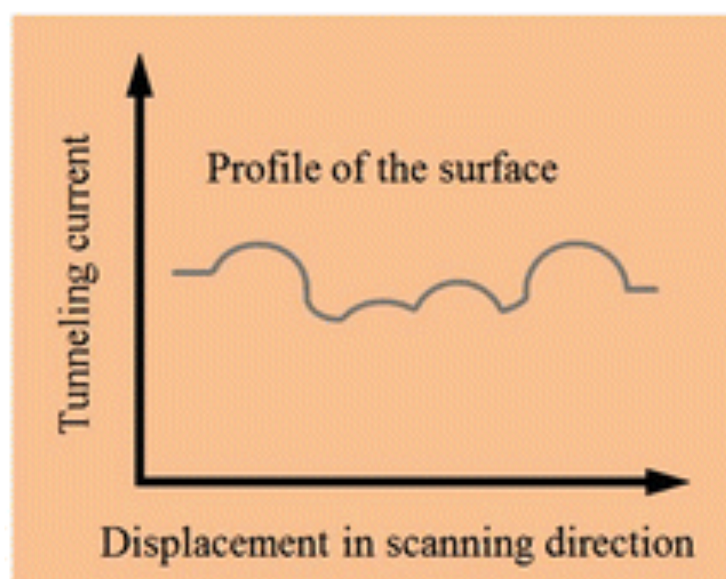
STM: Mode of Operation





- Image the surface with constant tunnel current and variable height
- Feed back loop help to maintain a constant current
- Surface (height) structure can detect





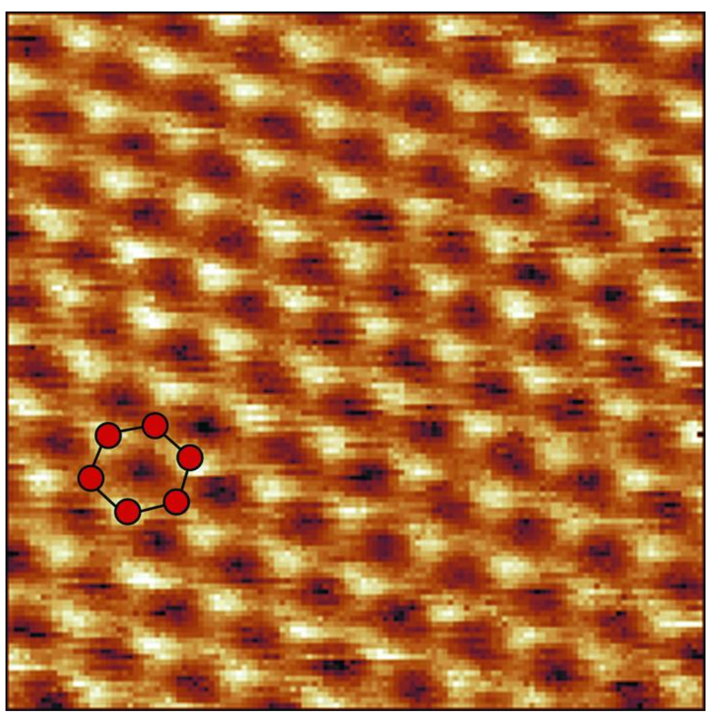
- Image the surface with constant height and variable tunnel current
- Electron density on the surface can detect

STM: Applications

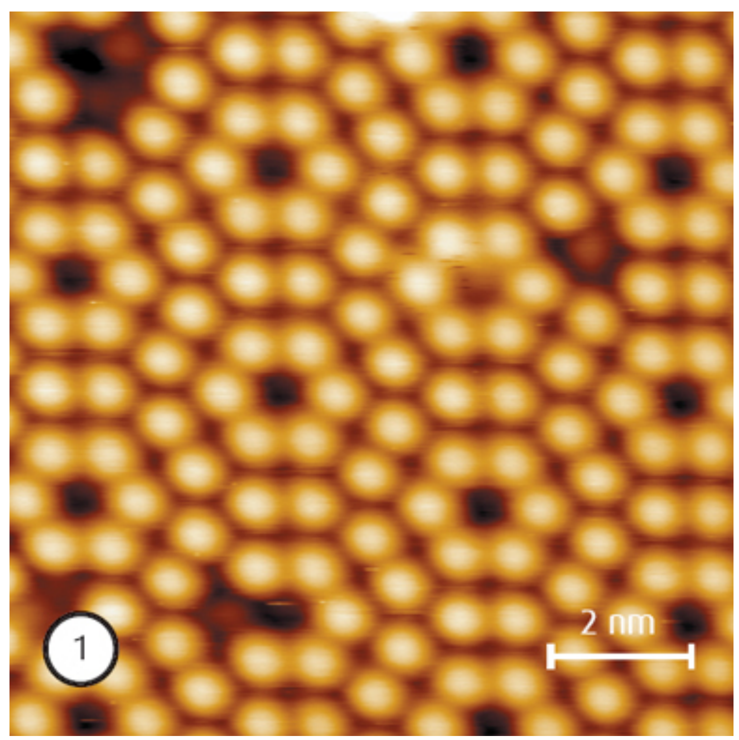
Widely used in nanotechnology:

- Image the surface structure
- Estimate surface roughness
- 3D images of the surface
- Locate the defect on the surface of the crystal
- Understand the electric structure of materials

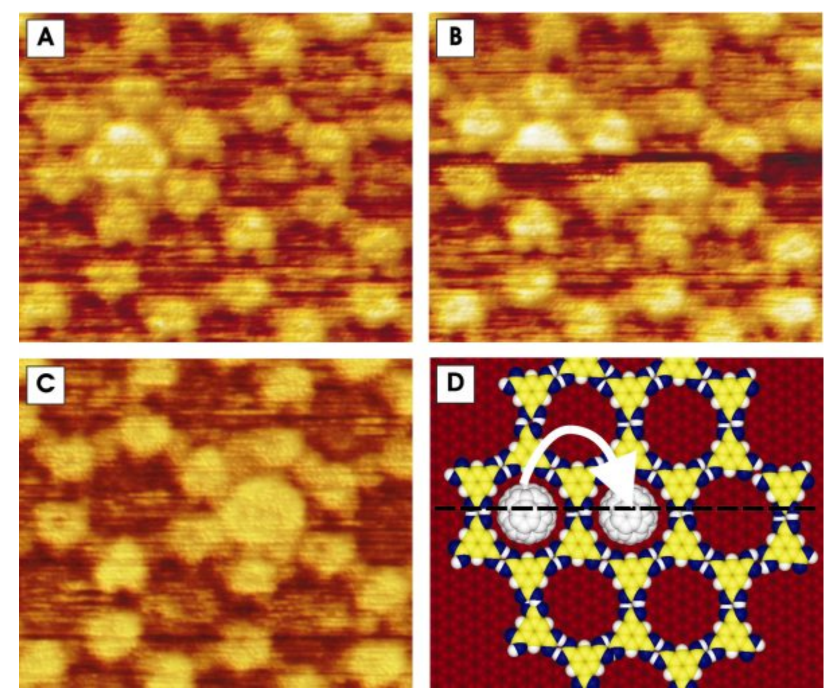
Graphite



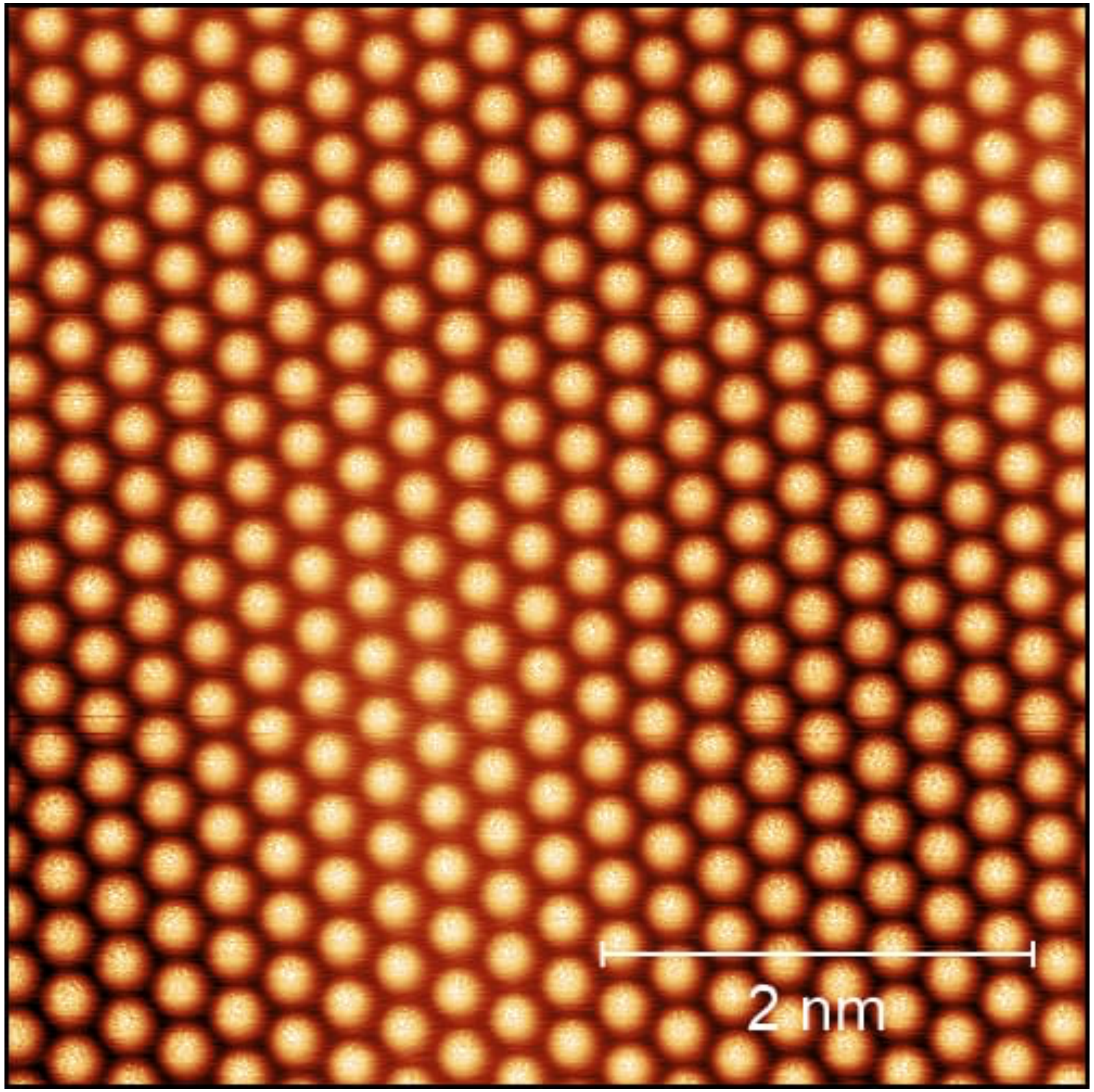
Silicon



C 60 Molecule



STM: Applications



Arrangement of atoms in Silver (Ag)

STM: Manipulating with atoms

Direct Measurement of *$|\psi|^2$ using STM and to manipulate atoms*