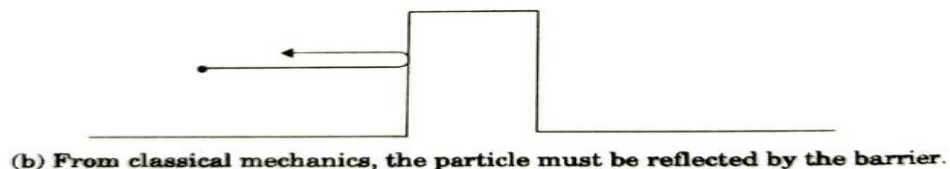


5.2 BARRIER PENETRATION AND QUANTUM TUNNELING.

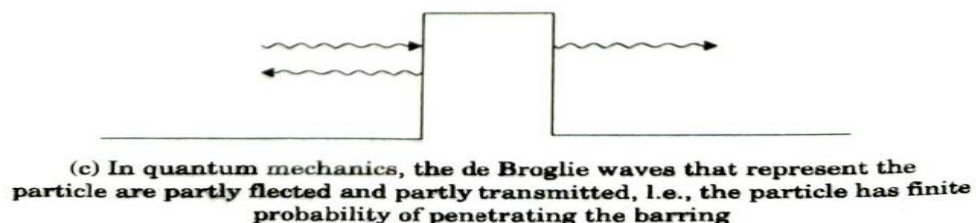
- According to classical ideas, a particle striking a hard wall has no chance of leaking through it. But, the behaviour of a quantum particle is different due to the wave nature associated with it.
- We know that when an electromagnetic wave strikes at the interface of two media, it is partly reflected and partly transmitted through the interface and enters the second medium.
- In a similar way the de Broglie wave also has a possibility of getting partly reflected from the boundary of the potential well and partly penetrating through the barrier.
- Fig. 5.4 shows a particle with energy $E < V$ approaching potential barrier of height V .
- An electron of total energy E approaches the barrier from the left. From the view-point of classical physics, the electron would be reflected from the barrier because its energy E is less than V .
- For the particle to overcome the potential barrier, it must have an energy equal to or greater than V .



(a) A particle with energy $E < V$ approaching a potential barrier.



(b) From classical mechanics, the particle must be reflected by the barrier.



(c) In quantum mechanics, the de Broglie waves that represent the particle are partly reflected and partly transmitted, i.e., the particle has finite probability of penetrating the barrier.

Quantum mechanics leads to an entirely new result. It shows that there is a finite chance for the electron to pass through the other side of the barrier.

It is noted that the electron tunneled through the potential barrier and hence in quantum mechanics, this phenomenon is called tunneling.

The transmission of electrons through the barrier is known as barrier penetration.

Expression for Transmission Probability

- Now let us consider the case of a particle of energy $E < V$ approaching a potential barrier of finite height and width as shown in fig. 5.5.
- The particle in region I has certain probability of passing through the barrier to reach region II and then emerge out on the other side in region III.
- The particle lacks the energy to go over the top of the barrier, but tunnels through it. Higher the barrier and wider it is, the lesser is the probability of the particle tunneling through it.

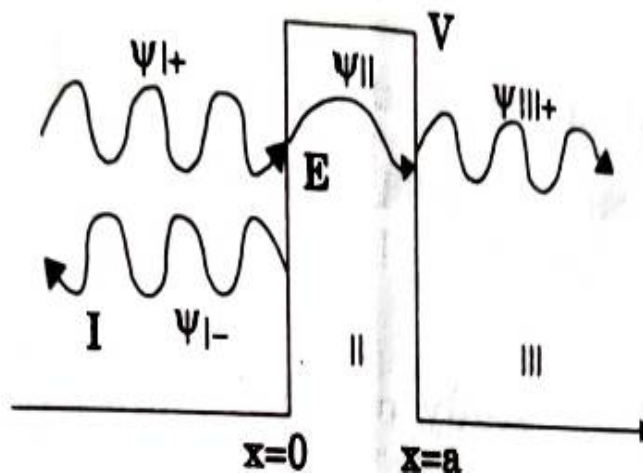


Fig.5.5 When a particle of energy $E < V$, approaches a potential barrier, the de Broglie waves that correspond to the particle are partly reflected and partly transmitted. That is the particle has a finite chance of penetrating the barrier

- Let us now consider a beam of identical particles, all having kinetic energy E . The beam is incident on the potential barrier of height V and width a from region I.
- On both sides of the barrier $V = 0$. This means that no forces act on particles in regions I and III.

The wave function Ψ_{II} represents the particle inside the barrier. Some of the particles end up in region III while the others return to region I.

Quantum mechanics shows that the transmission probability T for a particle to pass through the barrier is given by

$$T = \frac{\text{Number of particles transmitted}}{\text{Number of particles incident}}$$

This probability is approximately given by

$$T = T_0 e^{-2ka}$$

where $k = \frac{\sqrt{2m(V-E)}}{h}$ and a is the width of the barrier.

T_0 is a constant close to unity. It shows that the probability of particle penetration through a potential barrier depends on the height and width of the barrier.

Significance of the study of barrier penetration problems

- 1 Tunneling is a very important physical phenomenon which occurs in certain semiconductor diodes. In such diodes electrons pass through potential barriers even though their kinetic energies are smaller than the barrier heights.
- 2 The tunneling effect also occurs in the case of the alpha particles. The kinetic energy of alpha particle is only a few MeV but it is able to escape from a nucleus whose potential wall is perhaps 25MeV high.

- 3 The ability of electrons to tunnel through a potential barrier is used in the Scanning Tunneling Microscope (STM) to study surfaces on an atomic scale of size.

Terminology related to microscope

(a) Microscope

A microscope is an instrument which is used to view the magnified image of a smaller object which cannot be clearly seen with a naked eye.

(b) Optical microscope

It is a microscope which uses light radiation to illuminate the object.

(c) Resolving power

It is the ability of the microscope to show two closer objects as separated ones.

The resolving power is inversely proportional to wavelength of light used. In an electron microscope, beam of electrons are used to illuminate the specimen.

The wave length λ associated with these electrons is about 0.1\AA or less. Hence, its resolving power is very high. The minimum distance that can be resolved in the electron microscope is about 10\AA .

(d) Magnification Power

It is the ability of the microscope to show the image of an object in an enlarged manner.

$$\text{Magnification power} = \frac{\text{size of the image}}{\text{size of the object}} = \frac{\Delta}{F} \cdot \frac{D}{f}$$

In an optical microscope,

$F \rightarrow$ Focal length of objective lens in mm

$f \rightarrow$ Focal length of eye piece in mm

Δ - Length of microscope (16 cm)

D - Least distance of distinct vision (25 cm)

Thus, the magnification is about 1000X (one thousand times).

In the case of electron microscope, Δ is very large ($> 1 \text{ m}$)

F and f can be reduced to less than a millimetre. So, the magnification power of electron microscope is about 10^5X .

(e) Depth of focus

It is defined as the ability of the objective of microscope to produce a sharp focussed image when the surface of the object is not truly plane.

The deviation from plane surface occurs when the specimen is severely etched or when certain constituents of the structure are depressed or elevated from the etched surface.

5.2.1 Electron Microscope

It is a microscope which uses electron beam to illuminate a specimen and it produces an enlarged image of the specimen.

It has very high magnification power and resolving power when compared to optical microscope.

Principle

Like an optical microscope, its purpose is to magnify extremely minute objects. The resolving power of microscope is inversely proportional to the wavelength of the radiation used for illuminating the object under study.

Higher magnification as well as resolving power can be obtained by utilizing waves of shorter wavelength (λ).

Electron microscope uses electron waves whose wavelength is given by the formula $\lambda = \frac{12.25}{\sqrt{V}}$.

For $V = 10,000 \text{ V}$, $\lambda = 0.1225\text{\AA}$ which is extremely short. Electron microscopes giving magnification more than 2,00,000X are common in Science &

Technology Medical Research Laboratories.

An electron microscope consists of the following essential parts:

(i) Electron Gun. Its function is to provide a narrow beam of electrons of uniform velocity.

(ii) Electrostatic and magnetic lenses. Their function is to refract and properly focus the electron beam.

(iii) Fluorescent screen or photographic plate. They are used to receive the highly magnified image of the extremely small object being studied.

Types of Electron Microscopes

There are four types of electron microscopes. They are

- 1 Transmission Electron Microscope (TEM)
- 2 Scanning Electron Microscope (SEM)
- 3 Scanning Transmission Electron Microscope (STEM)
- 4 Scanning Tunneling Microscope (STM).

5.2.2 SCANNING TUNNELING MICROSCOPE (STM)

A scanning tunneling microscope, or STM, is a type of electron microscope. It is commonly used in fundamental and industrial research.

- It is an instrument used for imaging surfaces at the atomic level.
- Due to its high resolution, individual atoms within materials are routinely imaged and manipulated.

Principle

It is based on the concept of quantum mechanical tunneling electrons.

- In this technique, a sharp narrow conducting needle (probe) or tip is brought very near to the surface to be examined.

- A small voltage difference about 1V is applied between the tip and the surface of the material.
- This allows electrons to tunnel through the vacuum between them and results in tunneling current.
- Information about surface morphology is obtained by monitoring the tunneling current. The tip's position scans across the surface and it is usually displayed in image form

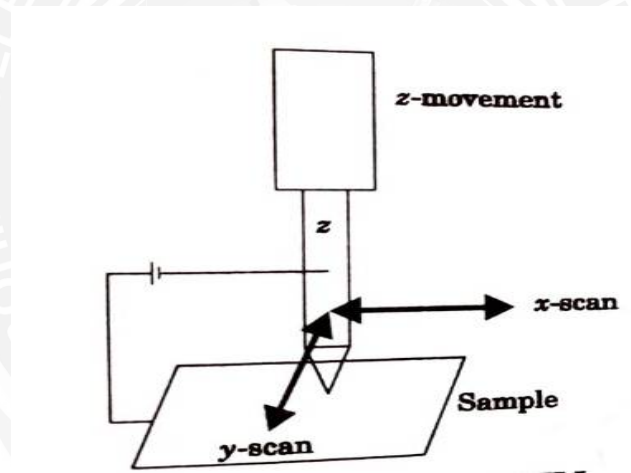


Fig. 5.6 Sketch of STM

Construction

The components of SIM include

1. Scanning needle tip
 2. Piezoelectric controlled height and surface (x, y) scanner.
 3. Coarse sample to tip control
 4. Vibration isolation system and
 5. Computer
- Needle tip for scanning the sample surface. It is often made of tungsten.

- Piezoelectric tube is provided with tip and electrodes. It is capable of moving X, Y, Z directions. It is used to maintain the tip position with respect to the sample and scanning the sample.
- Coarse sample to tip control is used to bring the tip close to the sample.
- Vibration isolation system: It presents any vibration or sound in the system
- The computer is used to acquire the data and it may also use for enhancing the image with the help of image processing as well as performing quantitative measurement.

Working

- The sharp metal needle is brought close to the surface to be imaged. The distance is of the order of a few angstroms.
- A bias voltage is applied between the sample and the tip. When the needle is at a positive potential with respect to the surface, the electrons can tunnel through the gap and set up a small "tunneling current" in the needle. This feeble tunneling current is amplified and measured.
- With the help of the tunneling current, the feedback electronics keeps the distance between tip and sample constant.
- Once tunneling is established, the tip's bias and position with respect to the sample can be varied and data are obtained from the resulting changes in current.

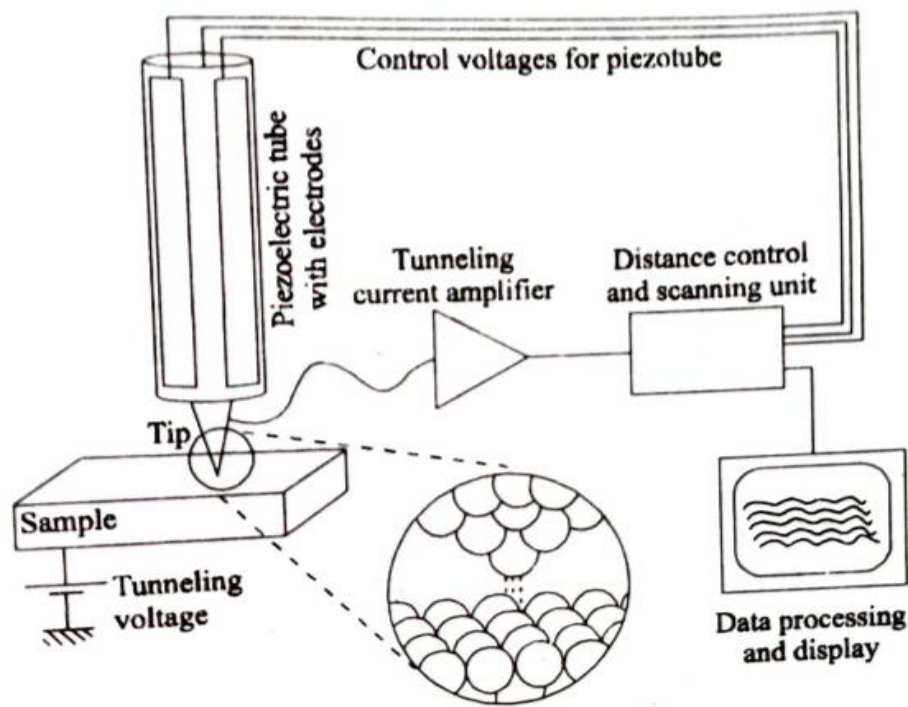


Fig.5.7 Scanning Tunneling Microscope

scanning

- If the tip is moved across the sample in the $x - y$ plane, the changes in surface height and density of states causes changes in tip current. These changes are mapped in images to present the surface morphology.
- This change in current with respect to position can be measured itself, or the height Z of the tip corresponding to a constant current can be measured. These two modes are called constant height mode and constant current mode, respectively.

Advantages of STM

- For an STM, good resolution is 0.1 nm lateral resolution and 0.01 nm depth resolution.

- The high resolution of STMs enable researchers to examine surfaces at an atomic level.
- Capable of capturing much more detail than other microscopes. This helps researchers better understand the subject of their research on a molecular level.
- STMs are also versatile. They can be used in ultra-high vacuum, air, water and other liquids and gasses.
- They will operate in temperatures as low as zero Kelvin up to a few hundred degrees Celsius.

Disadvantages of STM

STMs can be difficult to use effectively. There is a very specific technique that requires a lot of skill and precisions.

- STMs require very stable and clean surfaces, excellent vibration control and sharp tips.
- A small vibration even a sound, can disturb the tip and the sample together.
- Even a single dust particle can damage the needle.
- STMs use highly specialized equipment that is fragile and expensive.
- The electronics require for STM are extremely sophisticated as well as very expensive.

Applications of STM

- It is a powerful tool used in many research fields and industries to obtain atomic scale sample imaging and magnification.
- One innovative applications of STM recently found is manipulation of atoms.
- It is used to analyze the electronic structures of the active sites at catalyst surface

- STM is used in the study of structure, growth, morphology, electronic structure of surface, thin films and Nano structures.

