



Quantum tunneling: Concepts, theory, and applications

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Abstract

Quantum tunneling is one of the most surprising and important ideas in modern physics. It describes the ability of a particle to cross a barrier even when its classical energy is not sufficient to do so. This behaviour is completely impossible in classical physics, but it becomes natural when we understand the wave nature of matter in quantum mechanics. The purpose of this research paper is to explain the basic idea of tunneling, show how the concept comes from the Schrödinger equation, discuss mathematical solutions in simple steps, and explore the many practical uses of tunneling in modern technology, nuclear physics, semiconductor devices, scanning technologies, chemistry, and future quantum technologies. The paper also reviews historical development, limitations, and ongoing research trends. The language used is simple so that undergraduate students and new learners can understand the topic clearly.

Keywords: Quantum tunneling, potential barrier, wave function, alpha decay, STM, tunnel diode, quantum technology

Introduction

Quantum mechanics broke many of the classical ideas that had dominated physics for centuries. One of the most surprising discoveries was that particles do not behave only like small objects but also like waves. Because of this wave nature, they can show behaviour that looks strange to our classical intuition. One of these behaviours is quantum tunneling.

In classical physics, if a particle does not have enough energy to cross a barrier, it will always bounce back. For example, a ball cannot cross a wall unless someone pushes it with energy greater than the wall's height. But at the atomic and subatomic level, electrons, protons, neutrons, and other particles can sometimes appear on the other side of a barrier without having enough energy to climb over it. It is as if the particle "tunnels" through the barrier rather than crossing over it.

Quantum tunneling is extremely important today. Without tunneling,

the Sun would not burn,

electronic devices like tunnel diodes would not work,

scanning tunneling microscopes would not exist,

many chemical reactions would be slower,

alpha decay of heavy nuclei would be impossible.

Thus, tunneling is not just a strange theoretical idea. It is deeply connected with our daily technology and with the existence of stars themselves.

The goal of this paper is to explain tunneling from the ground level: starting from its history, basic theory, mathematics, and moving to advanced applications in modern technology. The style is simple to make the topic accessible.

Historical Background

The idea of tunneling came in the early 20th century when scientists were trying to understand radioactive alpha decay. Rutherford discovered that some nuclei release alpha particles, but no theory could explain how these particles escape from the strong nuclear potential barrier. Classically, the barrier was too high.

In 1928, George Gamow, and independently Gurney and Condon, proposed that alpha particles could escape not by climbing over the barrier but by tunneling through it. This was the first real application of tunneling.

Later, Fowler and Nordheim applied tunneling to electron emission from metal surfaces in strong electric fields, leading to the theory of field emission.

In the 1950s, Leo Esaki experimentally discovered electron tunneling in semiconductors, which led to the invention of the tunnel diode and later the Nobel Prize.

Since then, tunneling has become a key part of quantum physics.

Wave-Particle Duality and Tunneling

Tunneling cannot be understood without wave-particle duality. According to quantum mechanics:

Particles such as electrons behave like waves.

Their behaviour is described by a wave function $\psi(x)$.

This wave function can exist even in regions where classical energy is not enough.

In classical physics, if $E < V$ (energy is less than potential), motion is forbidden.

In quantum mechanics, $\psi(x)$ does not become zero. It decreases exponentially, but it does not vanish completely.

Because $\psi(x)$ continues inside the barrier, there is a small probability of finding the particle on the other side. This probability gives rise to tunneling.

The Schrödinger Equation and the Barrier Problem

The behaviour of quantum particles is described by the time-independent Schrödinger equation.

To understand tunneling, physicists study a simple potential barrier:

Region I: $E > 0$ outside the barrier

Region II: $V > E$ inside the barrier

Region III: again $E > 0$ on the other side

By solving the Schrödinger equation in each region:

Region I \rightarrow oscillatory solution

Region II \rightarrow exponential decay (evanescent wave)

Region III \rightarrow oscillatory solution again

The key point is:

$\psi(x)$ does not become zero inside the barrier \rightarrow so a particle can appear on the other side.

The tunneling probability T depends on:

barrier width (L)

barrier height ($V_0 - E$)

particle mass (m)

Smaller particles tunnel more easily.

Thinner barriers increase tunneling.

Lower barriers increase tunneling.

Even at absolute zero temperature, tunneling can happen.

Physical Interpretation of Tunneling

Tunneling shows that quantum particles do not have fixed positions or classical trajectories. Instead:

They exist as probability waves.

Their wave functions can spread across barriers.

The probability of appearing beyond the barrier is non-zero.

This behaviour is deeply connected with the uncertainty principle, according to which position and momentum cannot both be known perfectly. Because of this uncertainty, particles can "borrow" small amounts of energy briefly, allowing them to exist in classically forbidden regions.

Types of Quantum Tunneling

Several forms of tunneling exist in physics:

1. Electron Tunneling

Occurs in solids, semiconductors, metals, and nanostructures. Used in:

Tunnel diodes

Josephson junctions

Scanning tunneling microscopes

2. Alpha Particle Tunneling

Occurs in nuclear decay, explaining why heavy nuclei emit alpha particles.

3. Field Emission Tunneling

Electrons escape from metal surfaces due to strong electric fields.

4. Resonant Tunneling

Occurs when electron energy matches energy levels inside the barrier, increasing tunneling probability.

5. Photon Tunneling

Light waves can tunnel through barriers—basis of optical tunneling and frustrated total internal reflection.

Applications of Quantum Tunneling

This is one of the most important sections of the paper.

1. Nuclear Physics and Radioactive Decay

Tunneling explains alpha decay. Without tunneling, alpha particles trapped in a nucleus would never escape. The decay constant depends on tunneling probability, explaining why some isotopes are stable and others decay rapidly.

2. Quantum Tunneling in Stars (Proton-Proton Chain)

The Sun and other stars produce energy through nuclear fusion. Classically, protons cannot overcome their electrostatic repulsion at the Sun's core temperature.

Fusion inside stars is only possible because protons tunnel through the repulsive barrier.

Without tunneling \rightarrow no sunlight \rightarrow no life.

3. Tunnel Diodes

- Diodes are electrical semiconductor devices that allow electric current flow in one direction more than the other. The device depends on a depletion layer between N-type and P-type semiconductors to serve its purpose. When these are heavily doped the depletion layer can be thin enough for tunnelling. When a small forward bias is applied, the current due to tunnelling is significant. This has a maximum at the point where the voltage bias is such that the energy level of the valence electrons in the P-side and conduction-band electrons of the N-side are the same. As the voltage bias is increased, the two energy bands no longer line up and the diode acts typically.
- Because the tunnelling current drops off rapidly, tunnel diodes can be created that have a range of voltages for which current decreases as voltage increases. This peculiar property is used in some applications, such as high-speed devices where the characteristic tunnelling probability changes as rapidly as the bias voltage.
- The resonant tunneling diodes makes use of quantum tunnelling in a very different manner to achieve a similar result. This diode has a resonant voltage for which a current favours a particular voltage, achieved by placing two thin layers with a high energy conductance band near each other. This creates a quantum potential well that has a discrete lowest energy level. When this energy level is higher than that of the electrons, no tunnelling occurs and the diode is in reverse bias. Once the two voltage energies align, the electrons flow like an open wire. As the voltage further increases, tunnelling becomes improbable and the diode acts like a normal diode again before a second energy level becomes noticeable.

4. Scanning Tunneling Microscope (STM)

The scanning tunnelling microscope (STM), invented by Binnig and Heinrich R., may allow imaging of individual atoms on the surface of a material. It operates by taking advantage of the relationship between quantum tunnelling with distance. When the tip of the STM's needle is brought close to a conduction surface that has a voltage bias, measuring the current of electrons that are tunnelling between the needle and the surface reveals the distance between the needle and the surface. By using piezoelectric rods that change in size when voltage is applied, the height of the tip can be adjusted to keep the tunnelling current constant. The time-varying voltages that are applied to these rods can be recorded and used to image the surface of the conductor. STMs are accurate to 0.001 nm, or about 1% of atomic diameter. STM works by measuring tunneling current between a sharp tip and surface. Applications:

Imaging atoms on surfaces
 Manipulating single atoms
 Studying surface chemistry
 Nanotechnology

5. Flash Memory and MOS Devices

Electron tunneling is used to store charge in flash memory.

6. Josephson Junctions and Superconducting Qubits

Tunneling of Cooper pairs leads to:

Quantum computers
 Squid magnetometers
 Superconducting circuits

7. Chemical Reactions

Chemical reactions in the interstellar medium occur at extremely low energies. Probably the most fundamental ion-molecule reaction involves hydrogen ions with hydrogen molecules. The quantum mechanical tunnelling rate for the same reaction using the hydrogen isotope deuterium has been measured experimentally in an ion trap. The deuterium was placed in an ion trap and cooled. The trap was then filled with hydrogen. At the temperatures used in the experiment, the energy barrier for reaction would not allow the reaction to succeed with classical dynamics alone. Quantum tunnelling allowed reactions to happen in rare collisions. It was calculated from the experimental data that collisions happened one in every hundred billion.

In many reactions, protons or electrons tunnel through activation barriers. This explains:

Enzyme activity

Hydrogen transfer reactions

Low-temperature chemistry in space

8. Modern Nanotechnology

At nanoscale, barriers are extremely thin, so tunneling becomes common. Used in:

Carbon nanotubes

Quantum dots

Semiconductor superlattices

Tunneling Time and Experimental Studies

Scientists have long debated how long tunneling takes.

Some experiments show:

tunneling may be extremely fast, almost instantaneous

but probability is still small

Recent ultrafast laser experiments measure tunneling times of attoseconds (10^{-18} seconds).

Limitations and Challenges

Even though tunneling is powerful, there are limitations:

very sensitive to barrier width

reduces device stability if not controlled

makes miniaturization difficult because thin barriers cause leakage currents in nuclear contexts, tunneling probabilities are extremely small

Future Directions

Tunneling will play an important role in future technologies:

Quantum computers using tunneling qubits

Nano-electronic devices below 5 nm scale

Ultra-sensitive sensors

Tunneling-based solar cells

Quantum communication systems

Research is ongoing to control tunneling more precisely using lasers, engineered materials, and nanoscale devices.

Conclusion

Quantum tunneling is one of the most fundamental and surprising effects of quantum mechanics. It shows the limitations of classical physics and highlights the wave nature of particles. The concept originates directly from the Schrödinger equation and the properties of the wave function. Because the wave function spreads into forbidden regions, particles can pass through barriers that should be impossible to cross classically.

Tunneling is not just a theoretical concept. It has deep applications in nuclear physics, astrophysics, chemistry, and

modern electronic technology. Our understanding of stars, nuclear decay, scanning probes, memory devices, superconductors, and nanotechnology all depend on tunneling. As technology becomes smaller and more quantum in nature, tunneling will become even more important.

This paper used simple language to explain both the theory and the applications so that students and new learners can easily understand the concept. Quantum tunneling remains a central and fascinating part of quantum physics, influencing both fundamental science and real-world technology.

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