Macroscopic Quantum Tunnelling

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Theoretical Nexus
Nexus Day:A final Theory

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Tennis Ball Experiment

- Nobel Prize 2025 - John Clarke, Michel H. Devoret, John M. Martinis
- for demonstrating macroscopic quantum tunnelling

Tennis Ball Experiment - Weird?

- Of course that would never happen to life scale objects like tennis balls.
- But in quantum world, tiny particles such as electrons often pass through barriers that they normally should not be able to cross.
- This phenomenon is known as quantum tunnelling.

Until Now

- Until now, we thought such phenomenon existed only at the subatomic level among electrons and protons.
- But not anymore.
- These scientists have brought this quantum behaviour into the macroscopic world, not upto to a tennis ball, but something about the size that you can actually hold in the hand.
- This leads to the creation of most fundamental building block of quantum computing, the quantum bit or qubit.

Beginning of Quantum Mechanics

- In 1925, research paper by:
- Werner Heisenberg
- Max Born
- Louis de Broglie
- The beginning of quantum mechanics.

Three Key Phenomena

1. Quantum Tunnelling
2. Bose Einstein Condensate (state of matter)
3. Superconductivity

Quantum Tunnelling

- A solid wall is an impossible barrier no matter how much energy the tennis ball has.
- It can never pass through it unless it breaks the wall.
- But this is not how quantum tunnelling works.

How Tunnelling Works

- In quantum world, tunnelling happens only when the barrier is finite.
- One that a particle could cross if it had enough energy.
- However, even if it does not have sufficient energy, there is still a tiny probability that the particle will appear on the other side of the barrier.
- That is what is quantum tunnelling.

Example

- mound of sand and ball.
- Another Real example : vacuum tube with an emitter and collector plate.
- Insert a negatively charged mess, leads to repelling the electric field in the tube.
- Electron leaves energy to enter into the field before being pushed back.
- If energy is enough to cross halfway point, the remaining part of the field accelerates it towards the collector.
- But in quantum, something strange — electron does not have enough energy, few appear on other side.
- They vanish and appear on other side.

Applications

- Tunnelling microscope:
- It is the very tunnelling behaviour of electrons that forms the basis of the tunnelling microscope.
- Nuclear fusion in sun:
- It is because of tunnelling of protons that nuclear fusion occurs inside the sun producing energy.
- Alpha particles tunnel out from within a nucleus. That radioactivity takes place.
- It is common and natural event at quantum level.

Bose Einstein Condensate

- All known particles:
- Fermions family: electrons, protons, neutrons
- Bosons family:
- Photon (particles of light)
- Gluon (carry nuclear force)
- Higgs boson (gives mass to other particles)

Fermions vs Bosons

- Major difference between fermions and bosons lies in a property called spin.
- Fermions:
- Half integer spin
- Simply two spins
- Bosons:
- Integer spin
- Behave as if they do not have spin

Important Property

- Most important property of fermions is that fermions cannot exist in the same quantum state at the same time.
- Simply: two things cannot exist in the same place.
- Two fermions can never share the same set of quantum properties even if every other parameter is identical.

Bosons Behaviour

- The spin direction will be different.
- If one spins CW, others will spin in ACW.
- Bosons however do not have this restriction.
- Because of their spin nature many bosons can exist in exactly the same quantum state.
- It behaves as single quantum object rather than an individual particles.

Combination of Fermions

- Sometimes multiple fermions can combine to form a boson.
- Ex: Helium atom contains two e-, 2p+, 2 neutrons.
- Each of these particles is a fermion but since they are paired
- the spin simply cancel each other out.
- As a result the entire helium atom behaves as a boson.

Bose Einstein Condensate

- Special property of bosons are when they are cooled to extremely low temperatures
- they can enter a new state of matter known as bose einstein condensate
- often called 5th state of matter

Example of BEC

- Liquid helium cooled to -271 C
- its atoms settle into the same lowest energy state
- At that point all the atoms share one common quantum state
- and they no longer behave as separate particles
- instead they act collectively as a single quantum entity

Superfluidity

- In this condition helium exhibits a property known as superfluidity
- it can even climb up the walls of a container
- and flow out without any friction
- Best example of BEC

Superconductivity

- When certain materials are cooled to extremely low temperature
- the electrical resistance drops to zero
- this phenomenon is superconductivity
- Electric current is the flow of electrons

Conductors

- Metals are good conductors because outermost electrons are weakly bound
- hence large no of free electrons allow current to flow
- As they pass through the conductor they collide with atoms
- this collision creates obstruction called resistance

Cooper Pairs

- In certain special conductors crystal structure has unique property
- when cooled sufficiently the free electrons start pairing up
- known as cooper pairs
- an individual electron is a fermion
- but when two electrons form a pair their spins cancel
- and behave like a boson

Superconducting State

- When this conductor is cooled extremely low temp enters a state similar to BEC
- all cooper pairs move in perfect coordination
- flowing through material without scattering
- resistance drops to zero and material becomes superconductor

Quantum Tunnelling in Circuits

- Now imagine we have two superconducting circuits separated by a thin insulating layer
- Normally insulator should completely block any current
- This does not happen
- even when there is no voltage across the insulator
- a tiny current can still be observed flowing through it
- cooper pairs tunnel through the insulator by quantum tunnelling

Josephson Effect

- This quantum tunnelling current was first proposed by Brian Josephson
- known as Josephson effect
- Nobel Prize 1973
- two superconductors separated by insulator behaves like a macroscopic quantum object

Macroscopic Quantum Behaviour

- Normally quantum effects are seen only in small particles
- but here current behaves as a single quantum object
- it flows without voltage and shows wave nature
- circuits can tunnel through barriers with definite probability

Conclusion Extension

- This current also shows distinct discrete behaviour
- this means it could also exist in superposition
- this discovery brings quantum effects to macroscopic scale
- what was once thought impossible is now achieved

Tunnelling of electrons

Until now, we discussed phenomenologically. Here we use quantum mechanics.
Tunneling: particles pass through a barrier even if $E < V_0$.
Important for electrons (not much for ions/atoms).
Classical rate:

$$R \propto e^{-E_A/kT}$$

Quantum particles can tunnel even at $T = 0$.

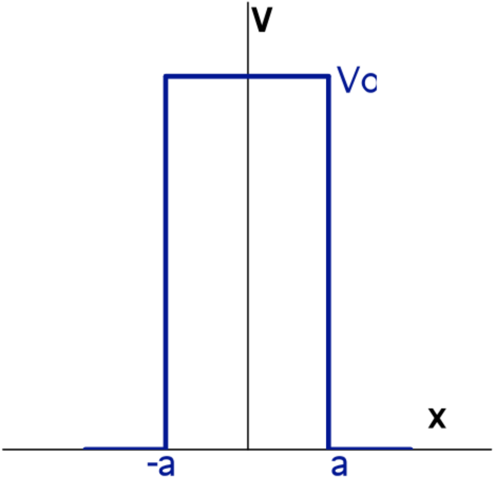
1D Potential Barrier

Consider a potential barrier (as opposed to a potential well)
The potential is constant V0 between x=-a and x=a, and zero outside of this region.
A particle starts on one side of the barrier, and we want to know the possibility of it crossing to the other side of the barrier.

$$V(x) = \begin{cases} V_0, & -a \leq x \leq a \\ 0, & \text{otherwise} \end{cases}$$

Particle has energy: $E < V_0$ so that classically it has no chance of crossing the barrier
Define transmission probability τ.

A simple Potential Barrier for tunneling analysis



Schrödinger Equation

Because of the simple nature of this potential, we can in fact solve the Schrödinger equation analytically for this setup:

$$H_{op}\psi = E\psi$$

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

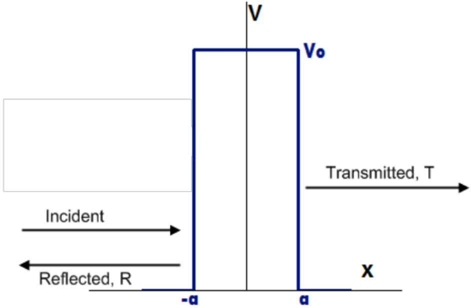
Piecewise function,then solution will
For $V = 0$:

$$\psi(x) = \begin{cases} e^{ikx} - Re^{-ikx}, & x < -a \\ Te^{ikx}, & x > a \end{cases}$$

$$E = \frac{\hbar^2 k^2}{2m} = \frac{p^2}{2m}$$

Reflection and Transmission coefficients R T

These determines the probability of reflection adn transmission throught the well.



Inside Barrier

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

$$\frac{d^2\psi}{dx^2} - \kappa^2\psi = 0$$

$$\kappa^2 = \frac{2m(V_0 - E)}{\hbar^2}$$

$$\psi(x) = Ae^{\kappa x} - Be^{-\kappa x}$$

Boundary Conditions

We now have four boundary conditions which let us determine the unknown coefficients A, B, R, and T.
Continuity at $x = \pm a$ gives coefficients.
Transmission coefficient:

$$|T|^2 = \frac{(2k\kappa)^2}{(k^2+\kappa^2)^2 \sinh^2(2\kappa a) + (2k\kappa)^2}$$

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For $\kappa a \gg 1$
$T \ll 1$:

$$T \sim e^{-2\kappa a}$$

Key Result

Transmission probability decays exponentially:

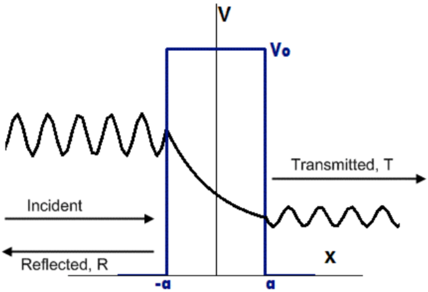
$$T \propto e^{-2\kappa a}$$

$$= e^{-2a\sqrt{\frac{2m(V_0 - E)}{\hbar^2}}}$$

Depends on:

- Barrier width
- $\sqrt{V_0 - E}$

Visual schematic of ψ for the tunneling problem.



We get a nonzero value of the wavefunction at the other side of the barrier, and thus an electron may exist past the barrier!

Conclusion

- Tunneling is purely quantum
- T decays exponentially
- Important in electronics and reactions

References

- *MIT OpenCourseWare* – Quantum Mechanics
- D.J. Griffiths, *Introduction to Quantum Mechanics*
- Lecture notes and academic materials
- image credit: MIT OpenCourseWare

Thank you