Quantum Tunnelling With and Without a Barrier:

Investigating Electron Dynamics in Quantum Tunnel Ionization

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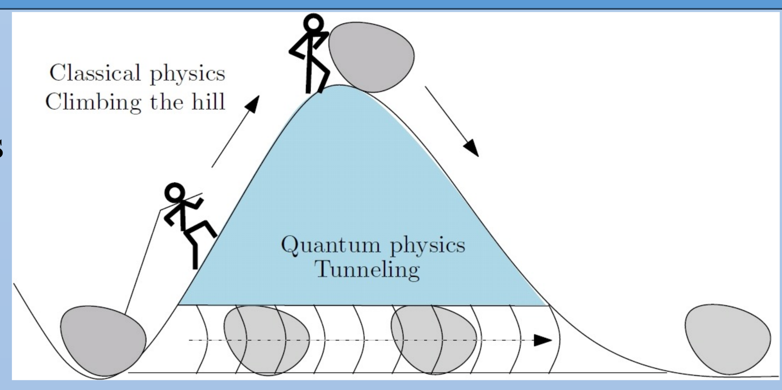
Abstract

Attosecond science explores ultrafast events that occur in just a few **attoseconds** (1 attosecond = 10^{-18} seconds). This groundbreaking field, awarded the **2023 Nobel** Prize in Physics, uses powerful **laser pulses** to study how **atoms** and **electrons** behave on incredibly short timescales. When intense laser beams interact with atoms, they distort the **Coulomb potential**, the force that normally keeps electrons bound to their nucleus, similar to how the moon orbits the Earth, but with much stronger forces. These strong **laser fields** give particles enough energy to be ionized, allowing them to **quantum tunnel**, a process where particles pass through barriers that classical physics says they shouldn't be able to overcome. Surprisingly, quantum tunneling can even happen when the **electric field is zero**, meaning the laser is not distorting the Coulomb potential, yet we still observe tunneling effect. This challenges our intuition and reveals new insights into atomic behavior under extreme conditions **(quantum tunnelling without a barrier!)**. Understanding these electron trajectories provides valuable knowledge about how matter behaves at the smallest scales.

Quantum vs Optical Tunnelling and Why it Matters?

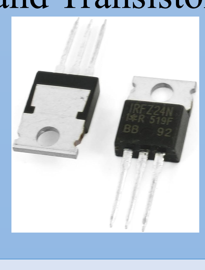
Quantum Tunneling



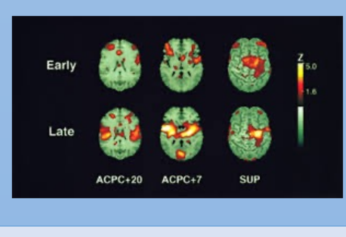
- **Definition:** Particles can pass through barriers despite lacking enough energy.
- **Cause:** Results from the wave-like behavior of particles in quantum mechanics.
- **Key Points:**
- **Wave-Particle Duality:** Particles behave as both waves and particles.
- **Probability:** Particles have a chance to "tunnel" through barriers.
- **Scale:** Significant at atomic and subatomic levels.
- **Why It Matters:** Essential for understanding fundamental processes in physics and enabling technologies like electronics.

- **Applications:**

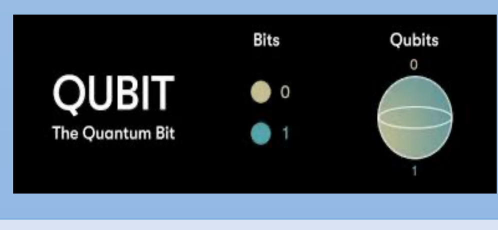
Semiconductors, and Transistors:



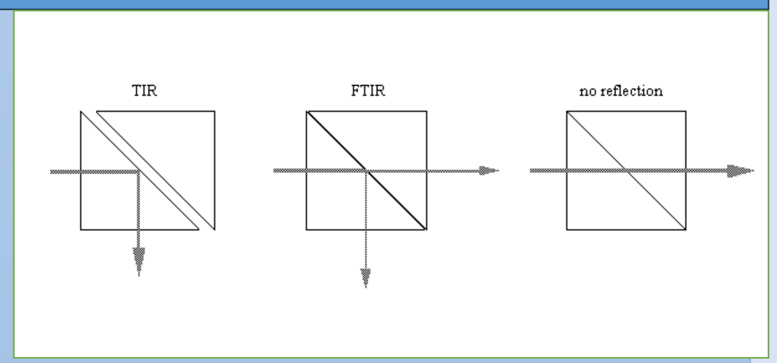
Radioactive Decay (Medical Imaging):



Quantum Computing:



Optical Tunneling

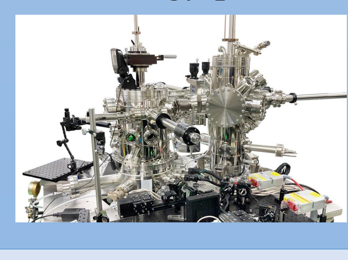


- **Definition:** Occurs when light encounters a barrier, allowing some light to "leak" through.
- **Cause:** Results from the evanescent wave that extends into the second medium despite total internal reflection.
- **Key Points:**
- **Frustrated Total Internal Reflection:** Demonstrated when prisms are pressed together.
- **Energy Transfer:** Light waves transfer energy to the second medium.
- **Scale:** Relevant in optics and photonics.
- **Why It Matters:** Essential for optical sensors and advanced photonic technologies.

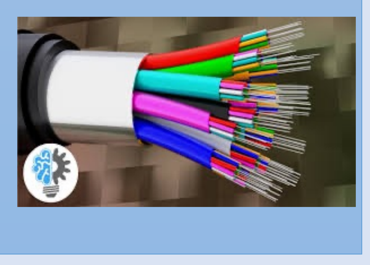
- **Applications:**

Optical Sensors:

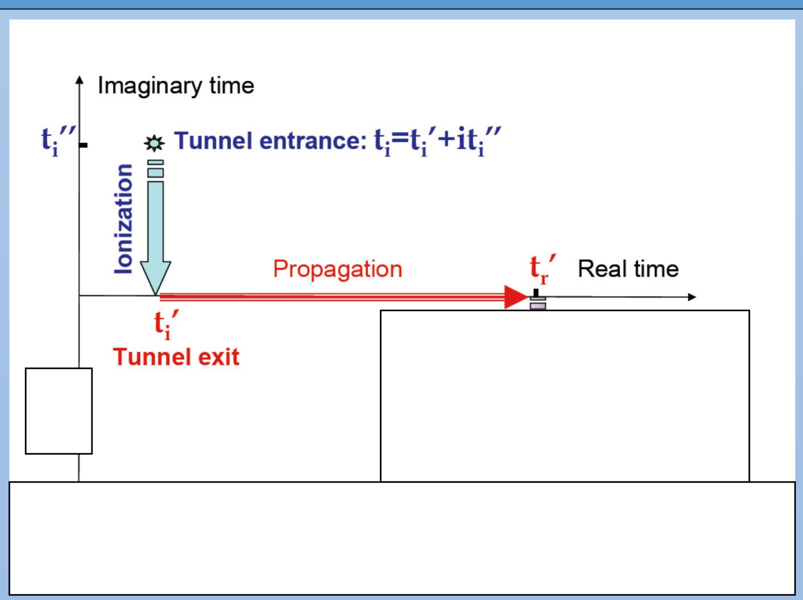
Scanning Tunneling Microscopy (nanotechnology/photonics):



Optical Fibers:



How Does Complex Time Work?



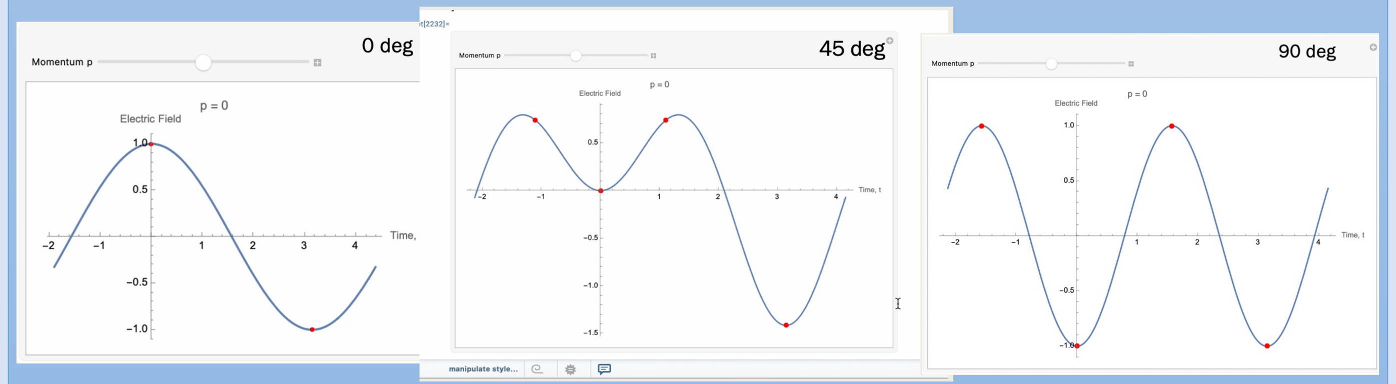
- **Time** is defined as the following: **Ionization/Tunnelling event** occurs in **imaginary time**.
- After the particle exits the tunnel, it **propagates** in **real time (**for the sake of this research ignore recombination)
- Interested in the electron's dynamics **inside the tunnel barrier**
- For the trajectories, the plot starts from right to left as Ionization time is defined as imaginary time shown above

Electric Field Strength of the Laser

- Biochromatic strong field driver is gradually replaced by its second harmonic.

$$E(t) = E_1\cos(\omega t) - E_2\cos(2\omega t) \qquad E_1 = E_0\cos\theta \text{ and } E_2 = E_0\sin\theta$$

- The mixing angle, θ, is responsible for the gradual replacement of the beam with its second harmonic (2ω)
- Varying the mixing angle θ from 0° to 90°, the electric field goes from the first harmonic (ω) to its second (2ω)
- When the mixing angle θ is 45°, it becomes an exact mixture of both, the first and second harmonic
- Where **Saddle point 2 becomes a minimum when the electric field is 0,** meaning no potential barrier is being distorted!



Saddle Points & Momentum

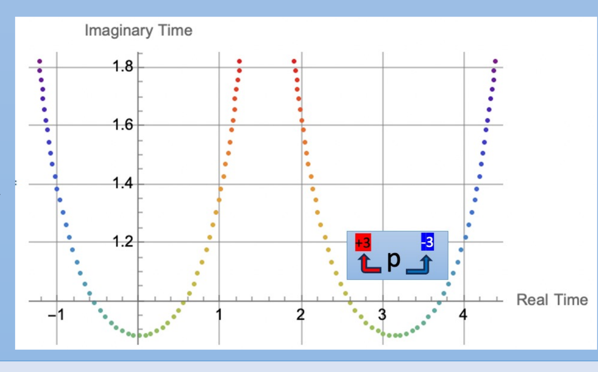
- **Trajectories:** Show how particles move through space and time.
- **Saddle Points**: Key values that provide **time solutions** to calculate the particle's motion.
- **Semi-Classical Actions**: Mathematical equations combining classical and quantum concepts. Saddle points provide **complex time value** solutions.

$$S(p,t) = \int_{-\infty}^{t} \left[\mathcal{I}_p + \frac{1}{2}\left(p + A(t')\right)^2 \right] dt' \,. \qquad \frac{\partial S}{\partial t}(p, t_s) = 0\,,$$

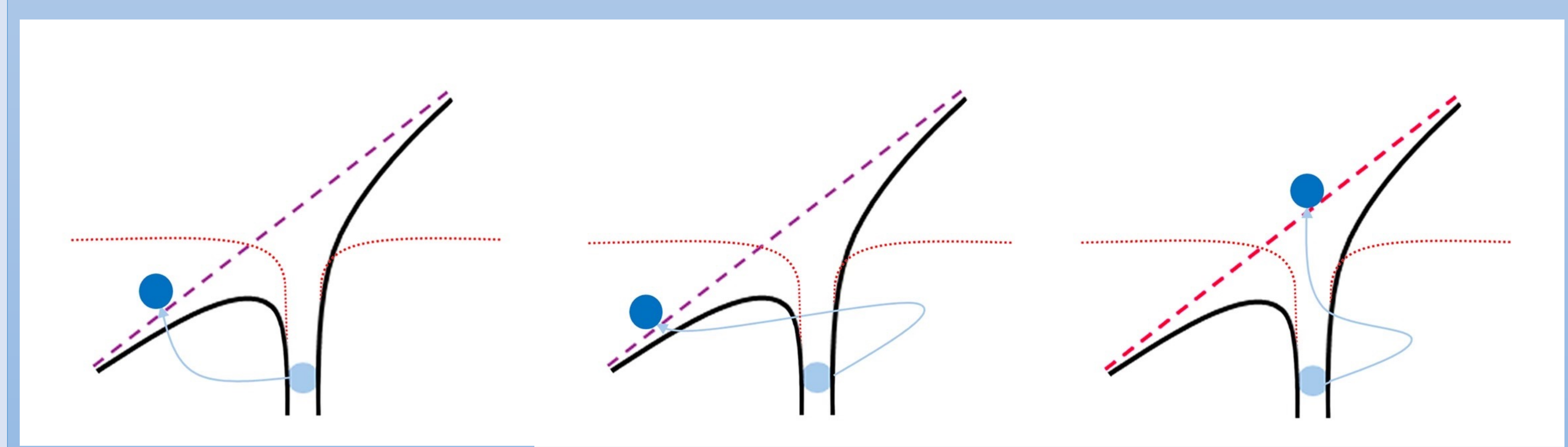
- **Classical Path Calculation**: complex time solutions are used to calculate the **classical path** the particle would follow.
- **Feynman's Path Integral:** A method that explains how dynamic processes in physics occur by considering all possible paths for particles transitioning between states.

Saddle Point Solutions

- These solutions depend on the momentum of electrons

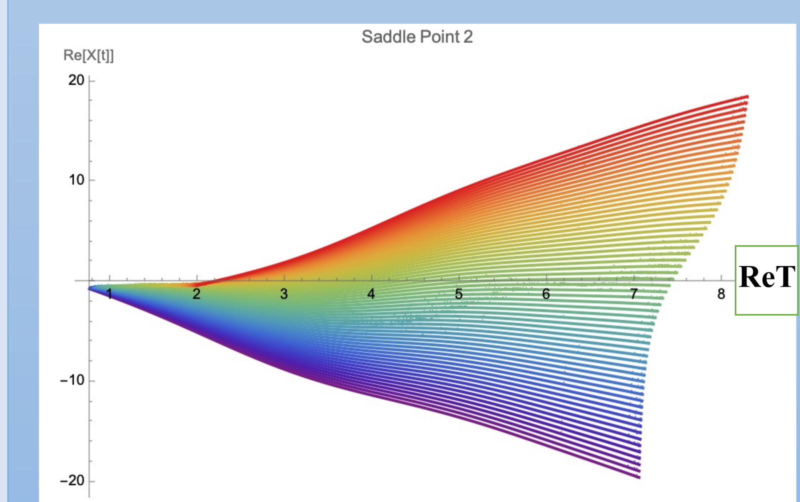


Quantum Tunnelling: Expectation vs Unintuitive Observations



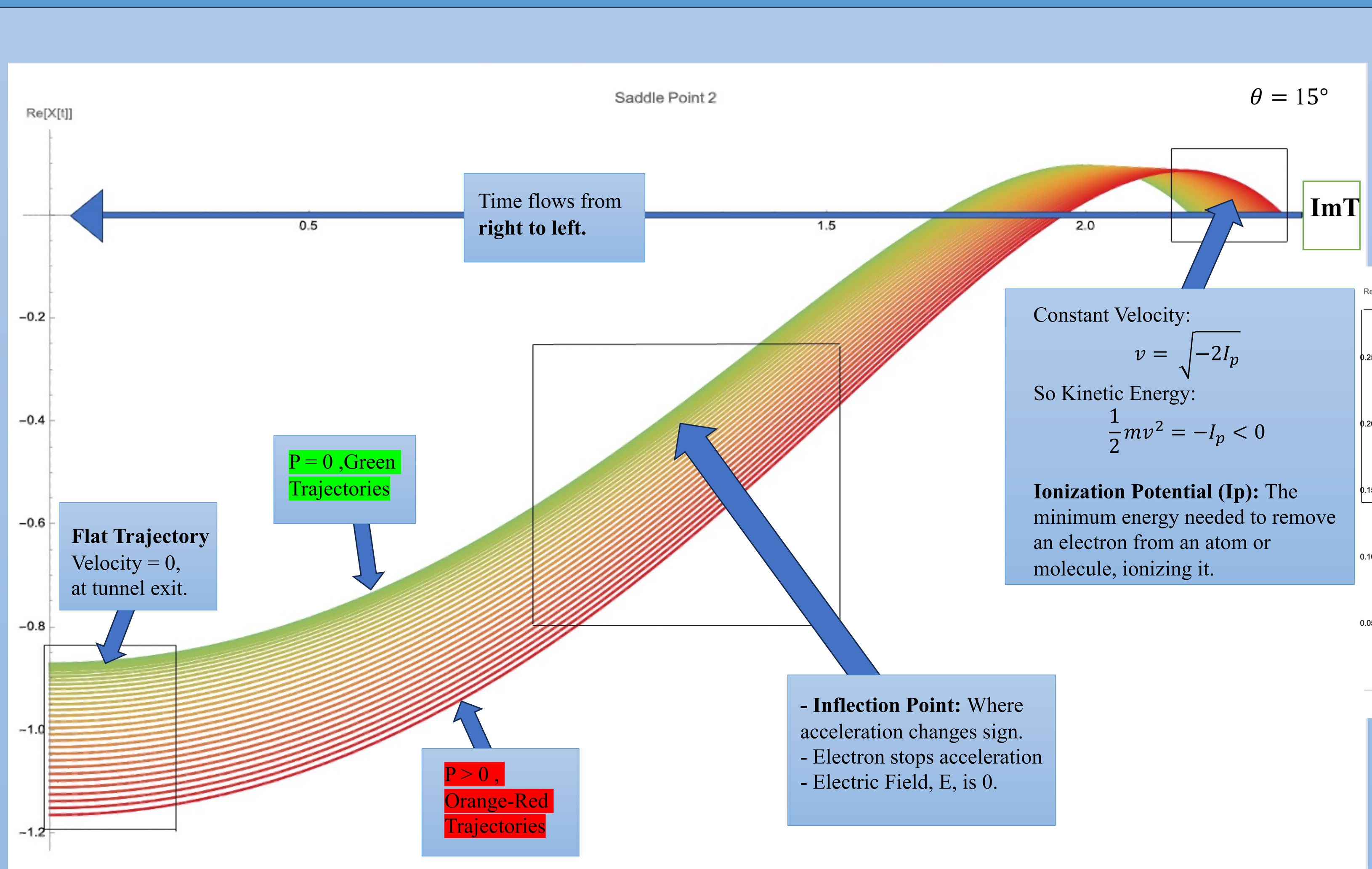
- Normally, particles can't enter regions with **higher energy barriers.**
- Sometimes, they **tunnel the "wrong way,"** moving toward these barriers despite lower energy.
- Inside, they **stop, change direction,** and tunnel out the other side.
- They emerge where **the barrier is distorted** or, at times, come out **in between both potentials**

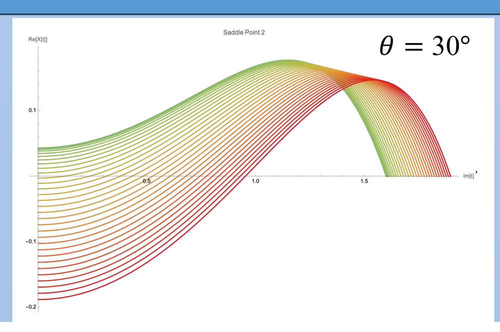
Trajectories Outside the Barrier

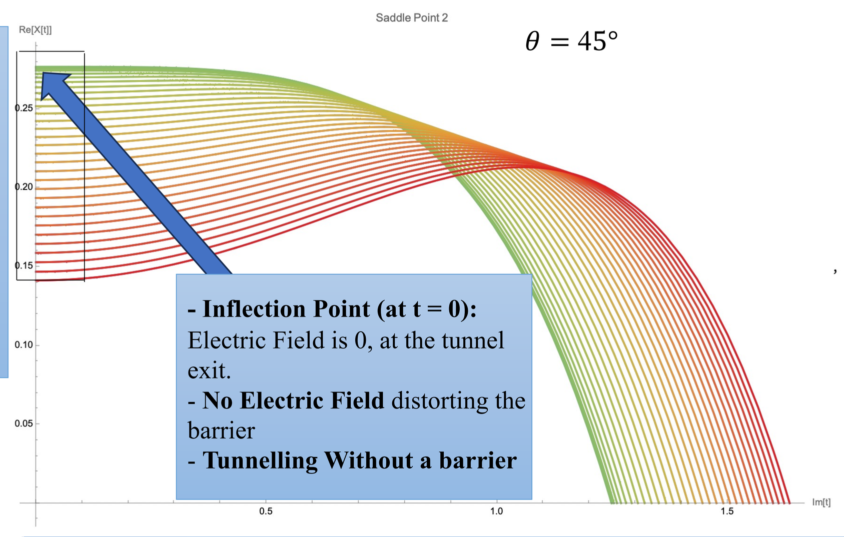


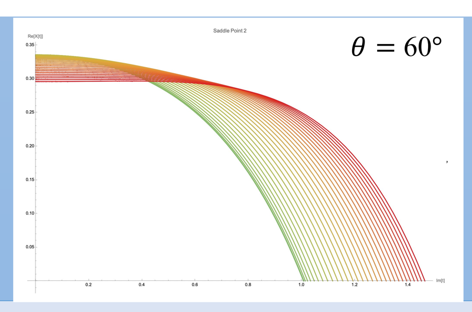
- Shows the propagation of the real electron trajectories after ionization against real time .
- **Color grading** reveals momentum effects:
- **Positive** moves forward, **Negative** moves backward.
- **Green** (momentum = 0) stays on the X-axis.

Trajectories Inside the Barrier









Conclusion

Main Findings:

- **Tunneling Behavior**: Particles can tunnel through energy barriers in unexpected directions, as well as changing directions whilst tunneling.
- **Inflection Points**: At points where acceleration changes sign, particles experience zero electric field, meaning the electron tunnels without a barrier.
- **Momentum**: The sign of momentum is directly related to the direction the particle travels to.

Personal Insights:

- **Understanding Dynamics:** Gained further knowledge of how the electron behaves whilst ionization and post-tunneling.
- **Impact on Quantum Mechanics:** Findings challenge traditional views on tunneling, posing even further questions on the subject.
- **Non-Classical Motion:** The ability of electrons to tunnel against energy gradients highlights the complexity of quantum mechanics.

Further Investigation:

- **Ongoing Research:** I will continue my exploration of this field through my third-year dissertation.
- **Electric Field Configurations:** I plan to investigate different electric field configurations to further enhance the presence of the second saddle point.
- **Tunneling Without Barriers:** I aim to deepen my understanding of the tunneling without a barrier phenomenon and exploring its physical interpretations and potential applications.

View 3D Plots of the Trajectories inside and outside the barrier (GIFS)

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