Unveiling Hidden Dynamics:
Speed Measurements of Classically Forbidden Motion

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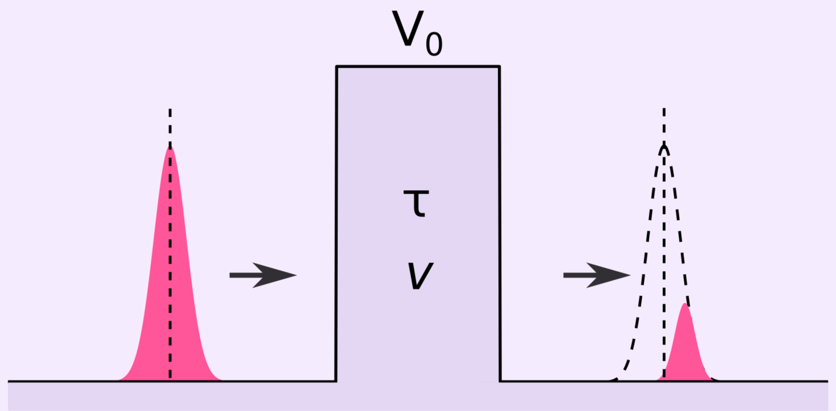
Quantum tunneling

How much time does the particle spend inside the potential barrier?

This question remains a subject of debate, with certain theoretical [1] and experimental [2] studies suggesting that **tunneling time decreases** as moving deeper into the classically forbidden region.



Here, we seek to provide clarity regarding the **speed of tunneling photons**, based on our recent theoretical paper [3], where we investigate **evanescent phenomena at a reflective step potential**.

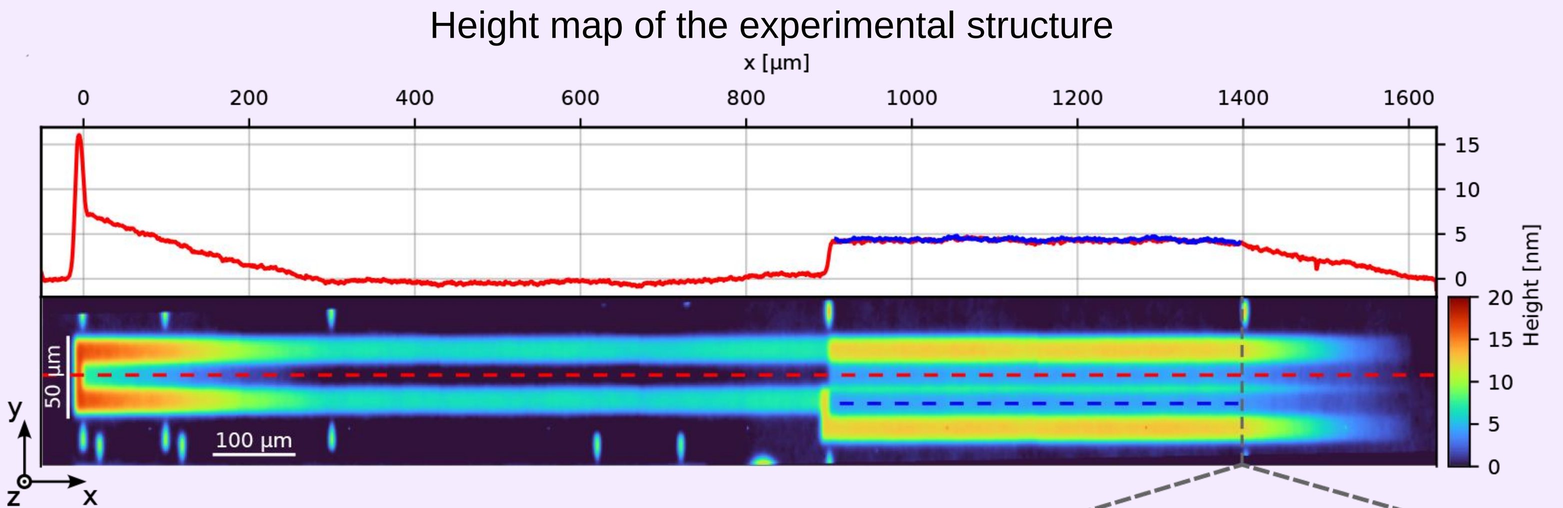
Coupled waveguides as a clock

How can we measure speed of the "tunneling" particles inside a potential step?

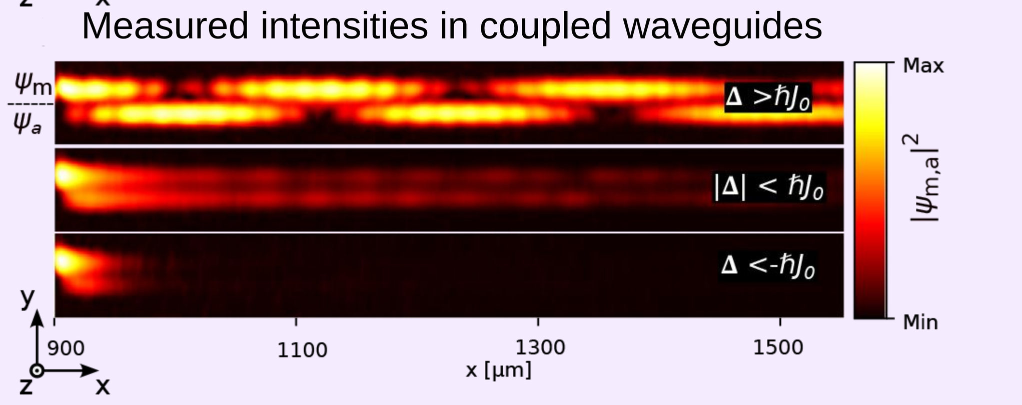
Experimental ingredients for speed extraction:

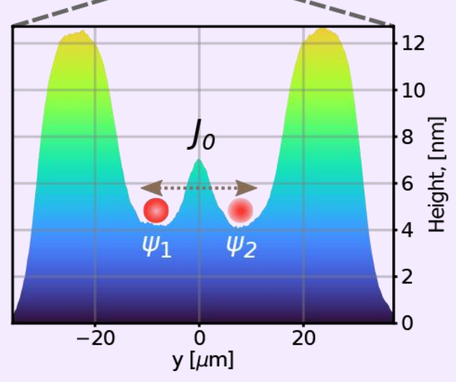
1. Potential step
2. Ability to change energy of incoming photons
3. Clock

Height map of the experimental structure



Measured intensities in coupled waveguides





Stationary 1D Schrödinger equations in coupling region:

$$E\psi_m = \frac{\hbar^2}{2m}\Delta\psi_m + V_0\psi_m + \hbar J_0(\psi_a - \psi_m)$$

$$E\psi_a = \frac{\hbar^2}{2m}\Delta\psi_a + V_0\psi_a + \hbar J_0(\psi_m - \psi_a)$$

Ansatz:

$$\psi_m \sim \cos(k_1 x)\, e^{ik_2 x}$$

$$\psi_a \sim \sin(k_1 x)\, e^{ik_2 x}$$

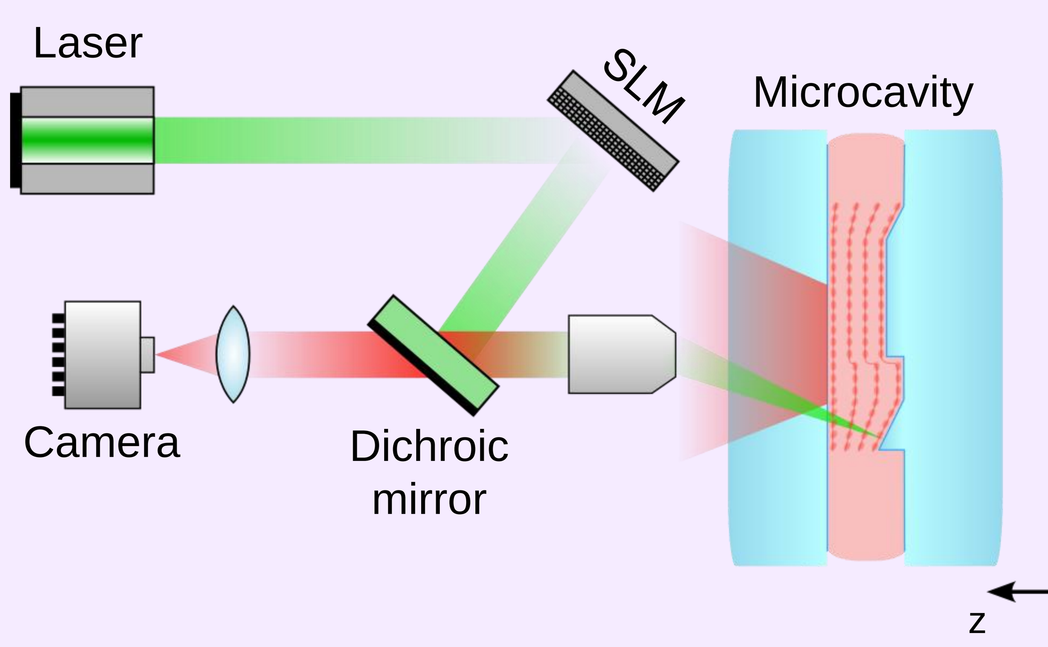
Total energy:

$$E = \frac{(\hbar k_1)^2}{2m} + \frac{(\hbar k_2)^2}{2m} - \hbar J_0 + V_0$$

Conclusion & Outlook

1. Measurements demonstrated speed increase when delving into the classically forbidden region, as it was predicted theoretically [3].
2. Phase and density gradients in quantum mechanical wave functions are found to play complementary roles in indicating particle motion.

Optical Microcavity Platform



2D trapped photon gas in microcavity [4]

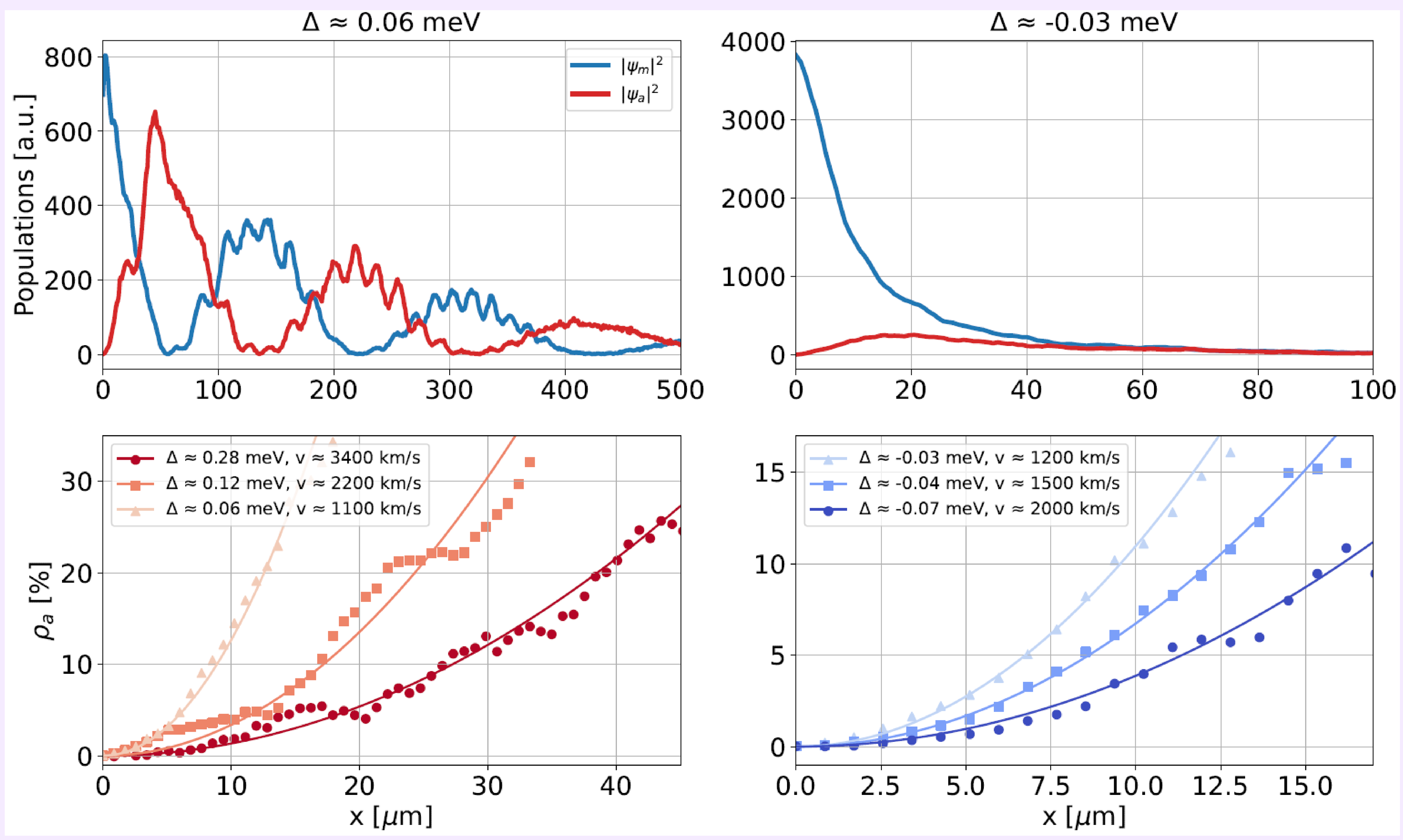
Photon Populations

$$\rho_a = \frac{|\psi_a|^2}{|\psi_m|^2 + |\psi_a|^2} \approx \left(J_0 \frac{x}{v}\right)^2$$

– *relative population*

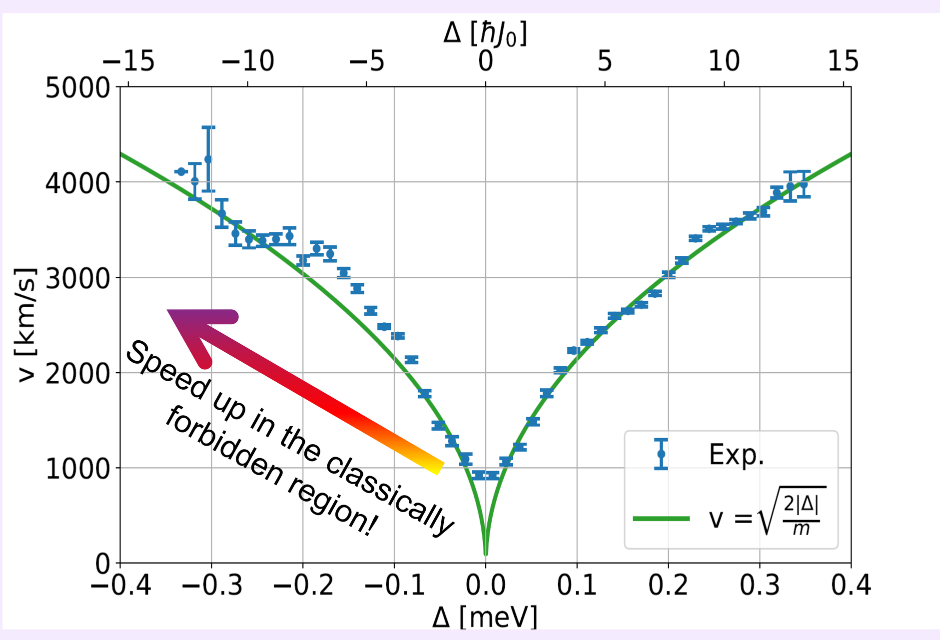
$$\Delta = E - V_0 + \hbar J_0$$

– *energy detuning*

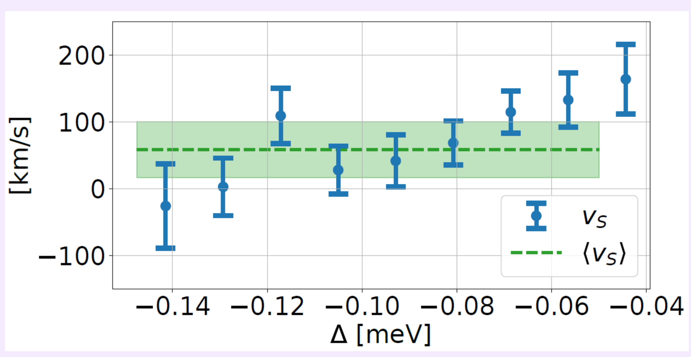


Speed Measurements

Coupled Waveguides Measurements



Phase Gradient Measurements



Bohmian perspective:

$$\psi(\boldsymbol{x}, t) = \sqrt{n(\boldsymbol{x}, t)}\exp(iS(\boldsymbol{x}, t))$$

$\boldsymbol{v}(\boldsymbol{x}, t) = \frac{\hbar}{m}\nabla S(\boldsymbol{x}, t)$ – velocity depends only on **phase gradients**.

However, we show that **density gradients** are indicators of motion in classically forbidden regions.

Video abstract is available:

[1] Dumont, R. S., et al. "The relativistic tunneling flight time may be superluminal, but it does not imply superluminal signaling." New Journal of Physics 22.9 (2020).
[2] Ramos, R., et al. Measurement of the time spent by a tunneling atom within the barrier region. Nature 583, 529–532 (2020).
[3] Klaers, J., Sharoglazova, V., & Toebes, C. (2023). Physical Review A, 107(5), 052201.
[4] Vretenar, M., et al. "Controllable Josephson junction for photon Bose-Einstein condensates." Physical Review Research 3.2 (2021)

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