Problem 17: Quantum-Droplet Analogy

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Problem Statement

Small droplets on the surface of a vibrating liquid can exhibit quantum-like behavior in analogy with the so- called pilot wave theory. Construct an experiment to test as many quantum analogies as possible, and discuss the theoretical and experimental limitations of this analogy. Can the analogy be pushed to cover phenomena involving entanglement, such as Bell inequality violations?

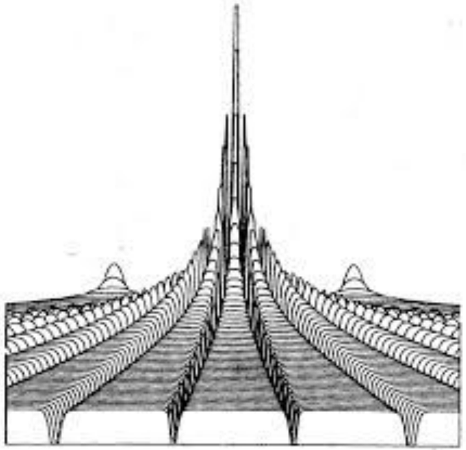
What is Bohmian Mechanics?

Causal interpretation of Quantum Mechanics

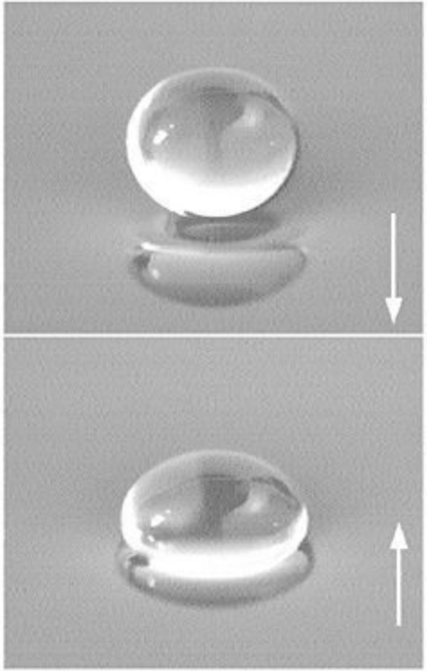
The wave function **guides** the particles, the particles **influence** the wave function through Schrodinger's equation.

$$\frac{d\mathbf{Q}}{dt}(t) = \frac{\hbar}{m}\,\mathrm{Im}\left(\frac{\nabla\psi}{\psi}\right)(\mathbf{Q},t).$$

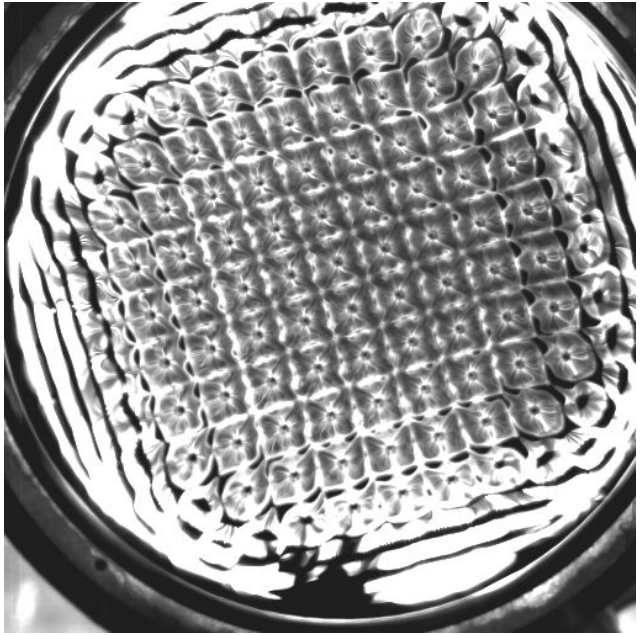
The central features: Far reaching potentials, initial uncertainty.



Why do these Droplets Bounce?



Avoiding Coalescence



Operating Sub Faraday Threshold

Experimental Setup and Procedure

We used a **Mechanical Vibrator**, **3 different dishes**, an **AC amplifier**, and a **tone generator app** on a phone to reproduce the ‘quantum droplets.’

We tried a variety of fluids:

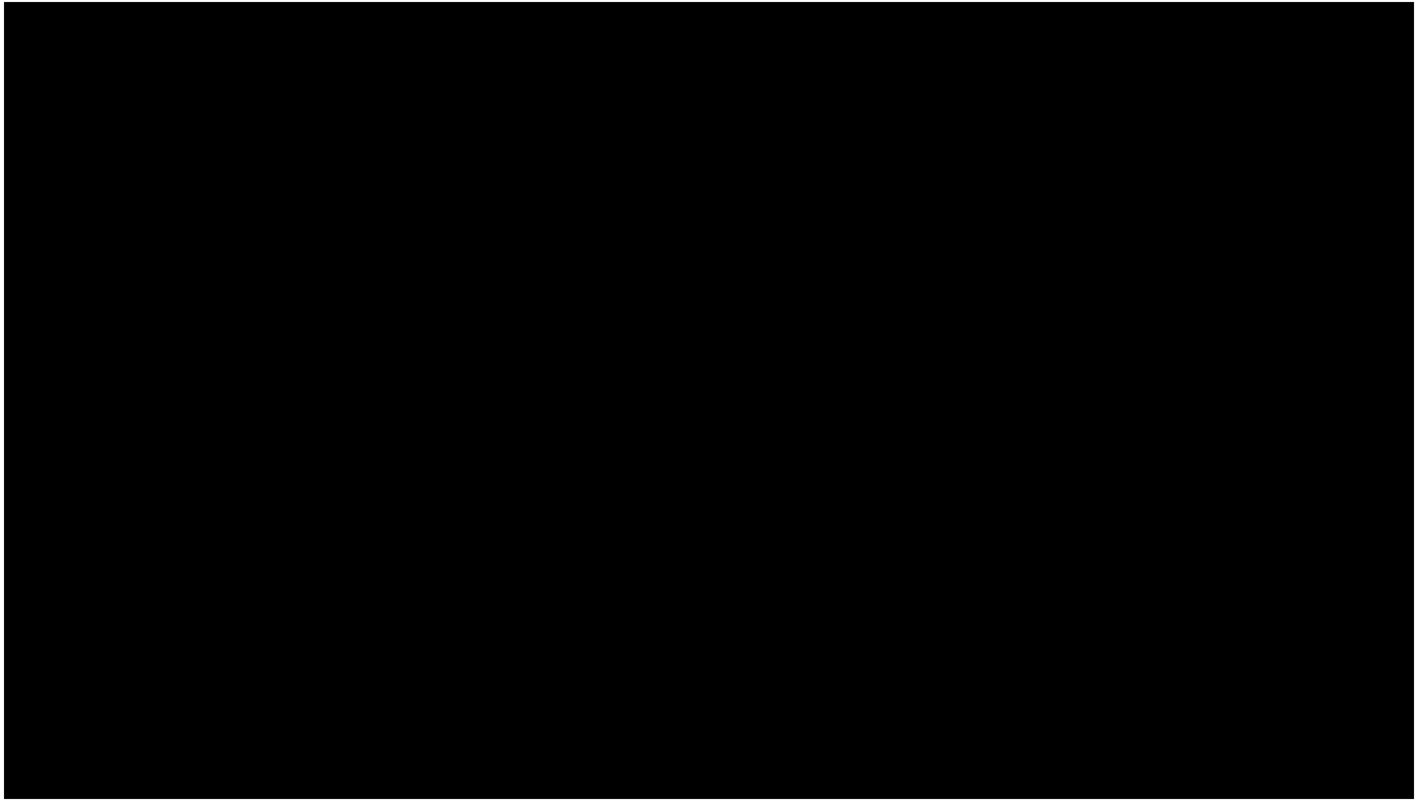
- Water + Varying concentrations of soap
- Lubricant Oil, ~30 cSt (kinetic viscosity)
- Silicone Oil, ~100 cSt (kinetic viscosity)

We had best results with the Lubricant and Silicone Oil

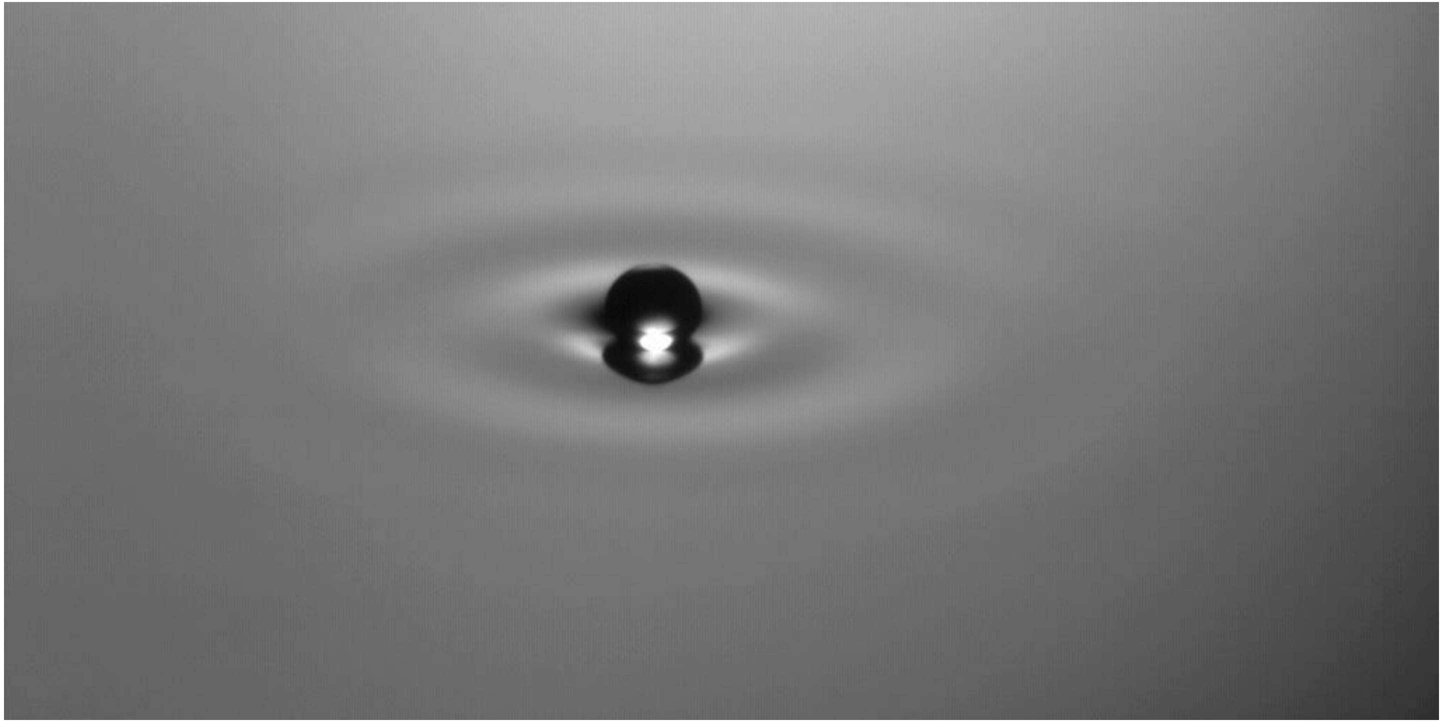
The Phenomena We Reproduce

- Bouncing Droplets: The meat of the experiment, as well as the conditions required for their production.
- Walking Droplets: Primarily showcasing the analogy to Bohmian Mechanics
- Crystal/Lattice Configurations: Showcase bound states and form a cornerstone of the analogy to quantum mechanics.
- Quantum corral: Accidentally noticed by us, we initially thought it was experimental error.

Bouncing Droplets



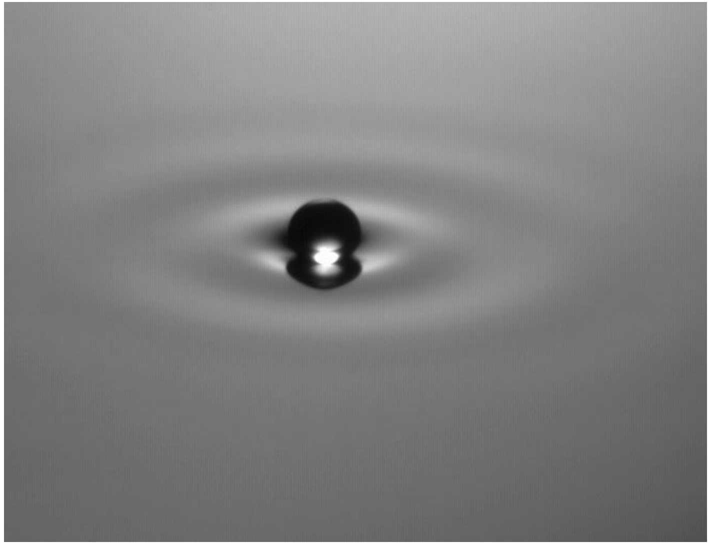
Produced and captured by other researchers



We were able to see these waves with a stroboscope! But our phone cameras were not able to operate well while the stroboscope was running.

Discussion, Implications, and Analogies

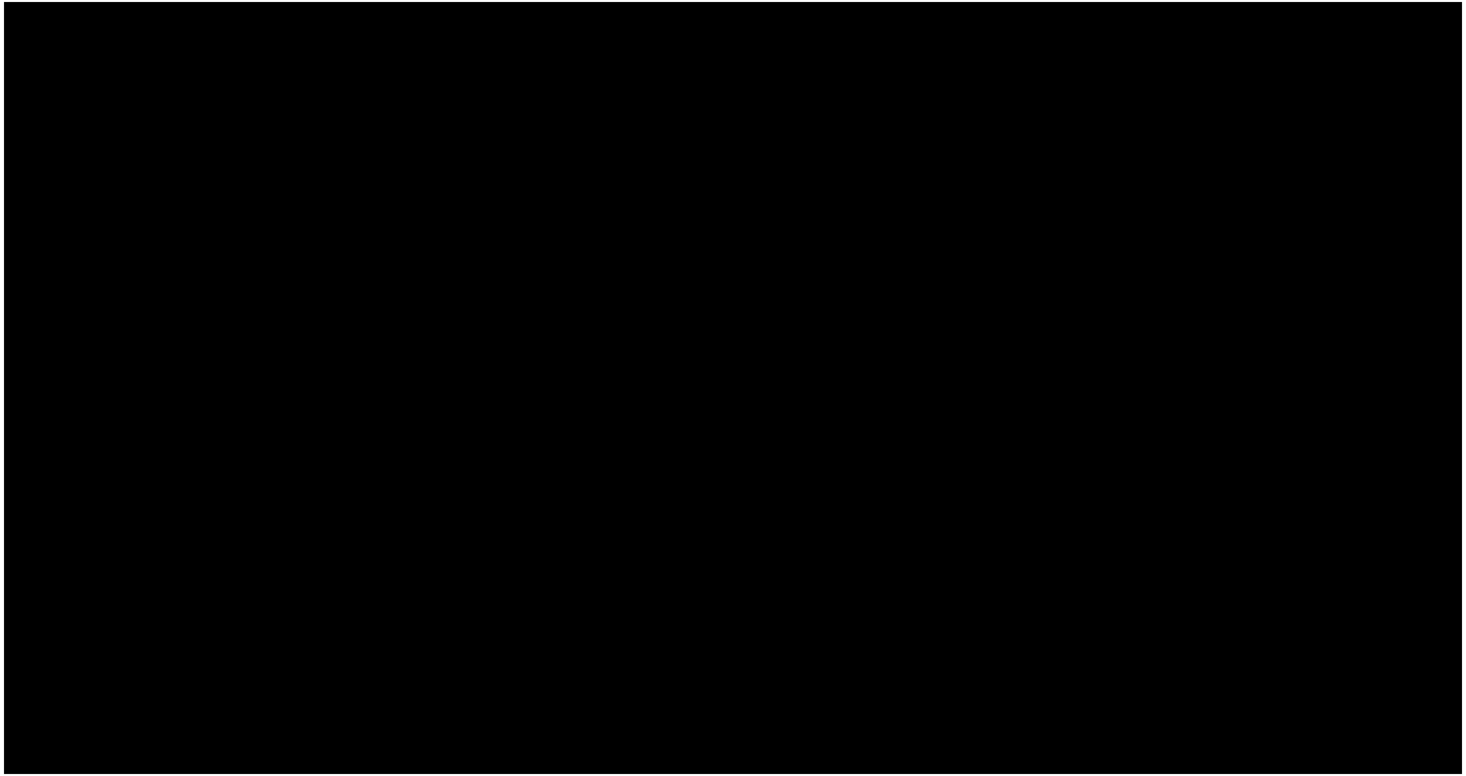
- The optimal frequency range for droplets of size on the order 1 mm is 50 Hz, we got good behaviour at 30 and 70 as well. (There are optimal frequencies, but others produce subharmonically modulated bounces, Veritasium's own video actually shows this kind of behavior!)



- The walking regime is quite slim and requires being barely below the Faraday Threshold

- The existence of the wave particle coupling justifies our analogy to Bohmian mechanics.

Walking Droplets



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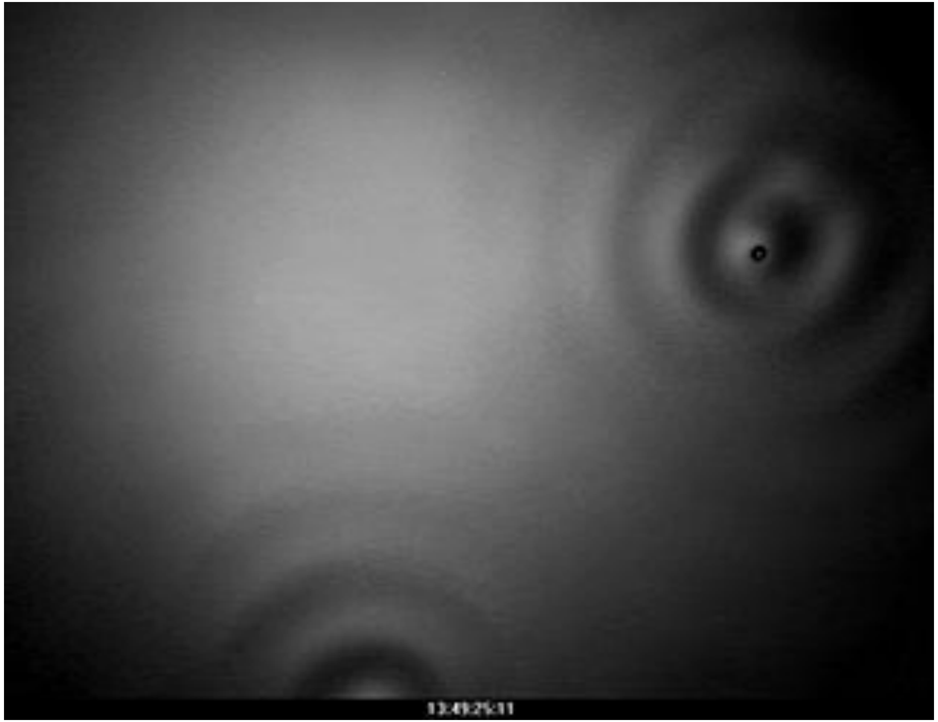
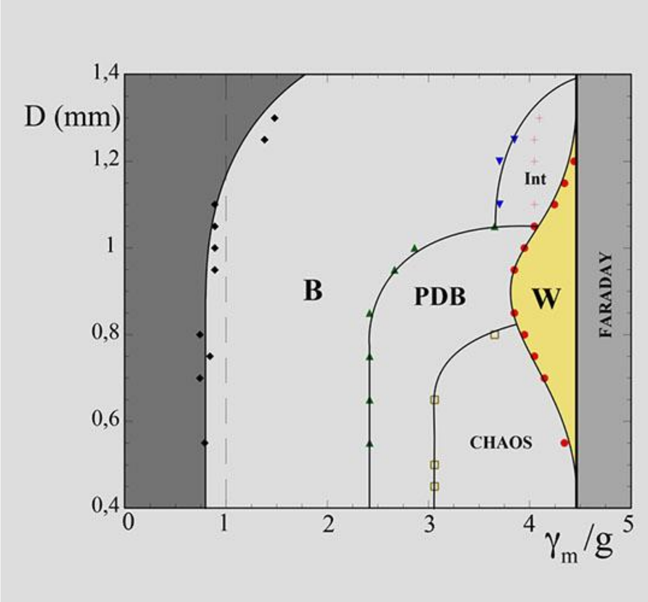


Discussion, Implications, and Analogies

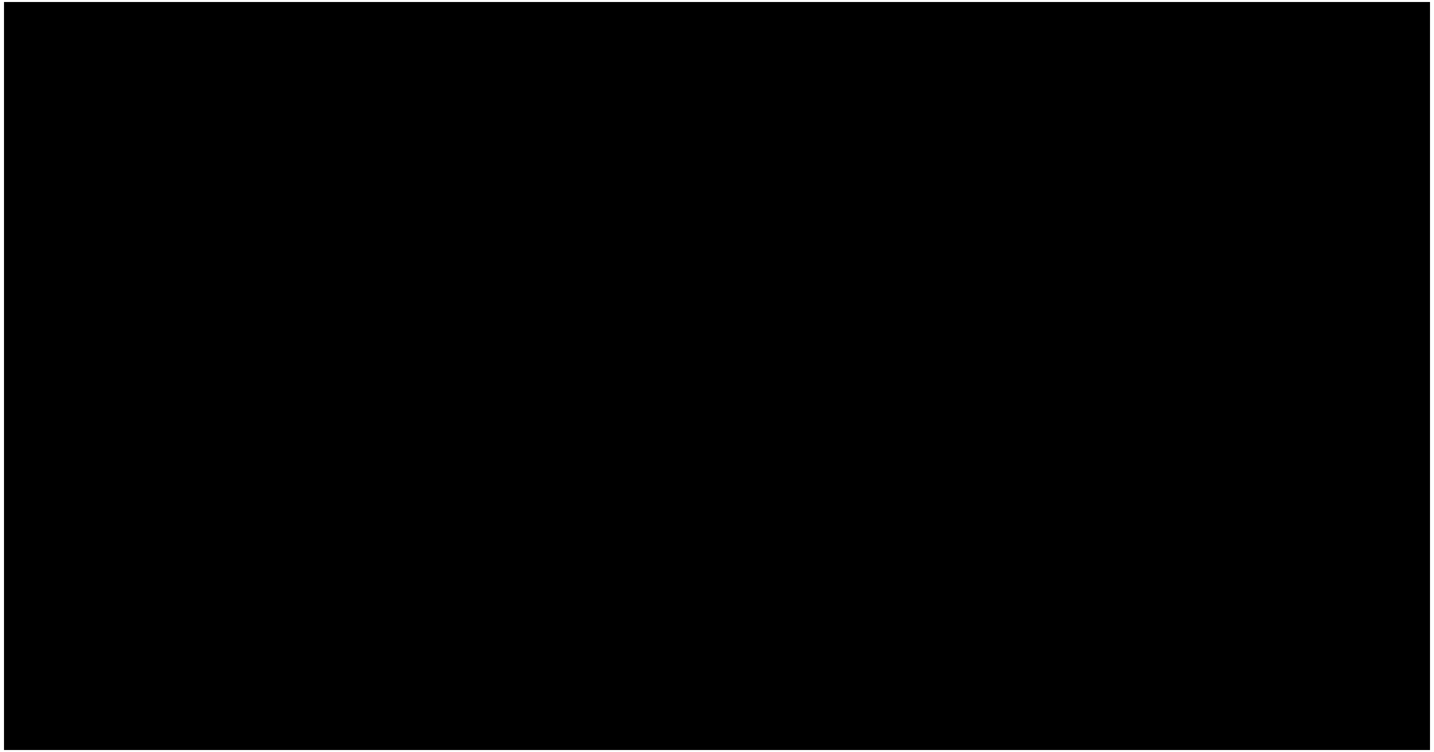
- The walking phenomena most clearly shows the wave **guiding** the particle as alluded to in Bohmian mechanics.

- The walking regime is quite slim and requires being barely below the Faraday Threshold and in the right droplet size.

- Spatial dependency of the amplitude leads to Walking behaviour in specific regions.



Crystal/Lattice Configurations



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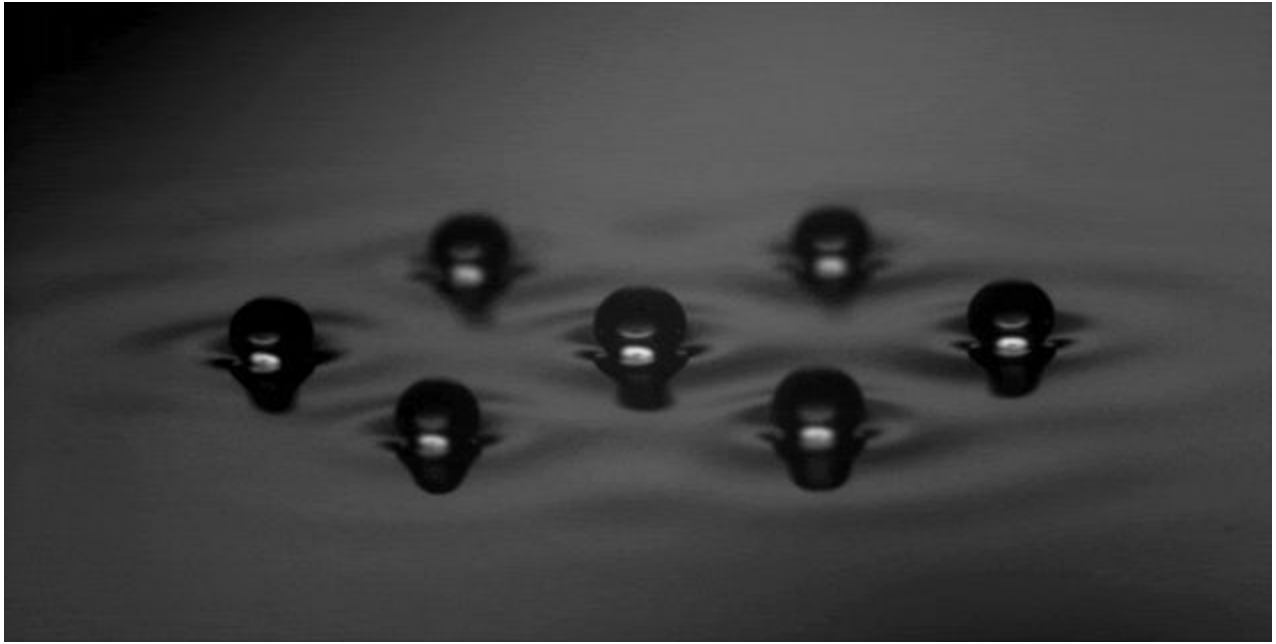


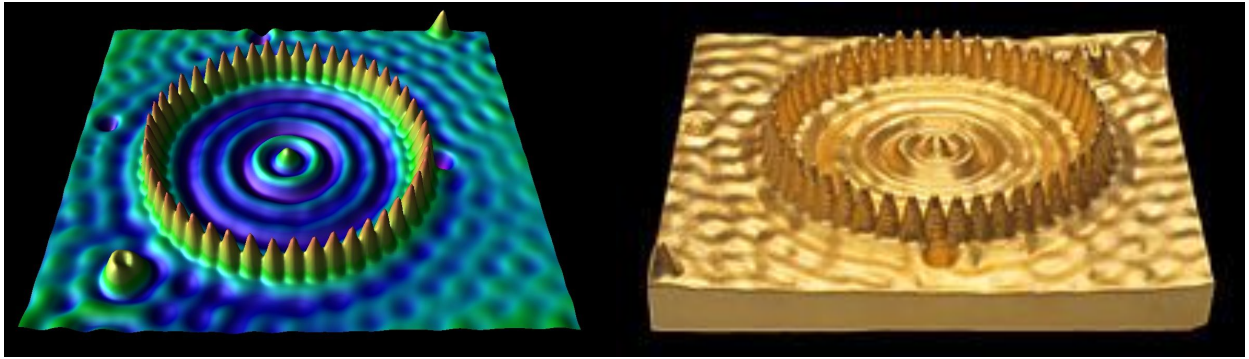
Discussion, Implications, and Analogies

- Classically bound states do not exist.
- The stability of crystals is purely a quantum phenomena
- The momentum transferred is related to the average slope experience in a bounce, in relation to Bohmian theory. Crystals settle into zero average slope.
- The droplet typically settles into the first antinode of the wave produced by its nearest neighbour
- Not observed by us, but the crystals also behave analogous to real ones under vibrations.

Quantum Corral

What is it? A ring of atoms arranged in an arbitrary shape on a substrate reflect electrons into a wave pattern and generate specific regions of high probability.

The analogy - There are specific locations within the bath where the droplets are more likely to be found similar to electron in Quantum Corral.



This behaviour occurred most of the time and we pegged it to be experimental error in delicately setting up the experiment until we discovered this analogy. Unfortunately we did not record it **:(**

Experimental Shortcomings and Future Additions

- The Size of the Dish
- The Levelling of the Dish
  - Spatial dependence of Faraday Waves
- Weight Management
- Rigidity of the dish
  - Resonance of the dish itself
  - Spatial dependence of Faraday Waves
- Unexpected behavior from potentials
- For the future
  - Piezoelectric Droplet Generator
  - Injecting ferrofluids into the droplets to see quantized orbits
  - Rotating the dish to simulate magnetic fields
  - More fluids around the recommended range of ~50 cSt

Theoretical Considerations and Limitations

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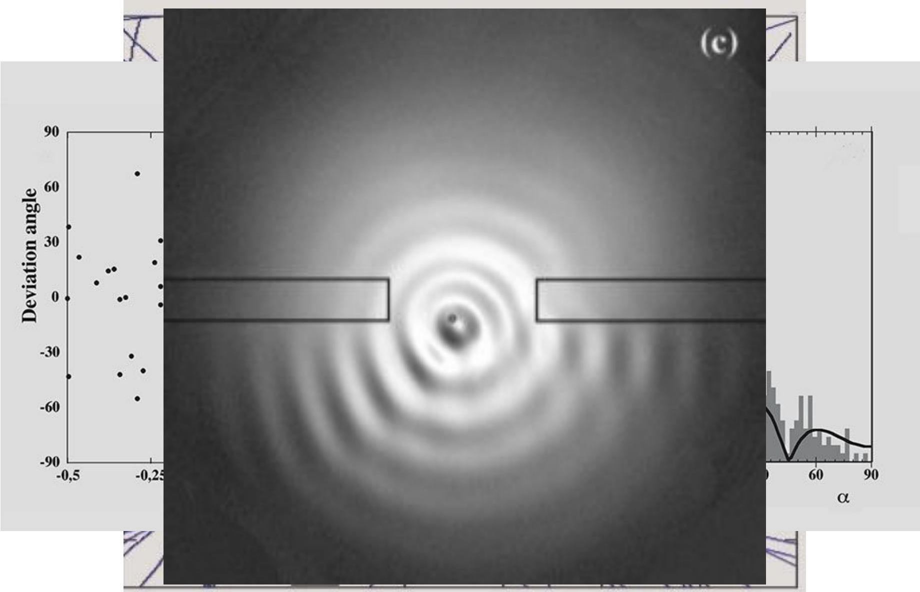
Single and Double Slit Diffraction

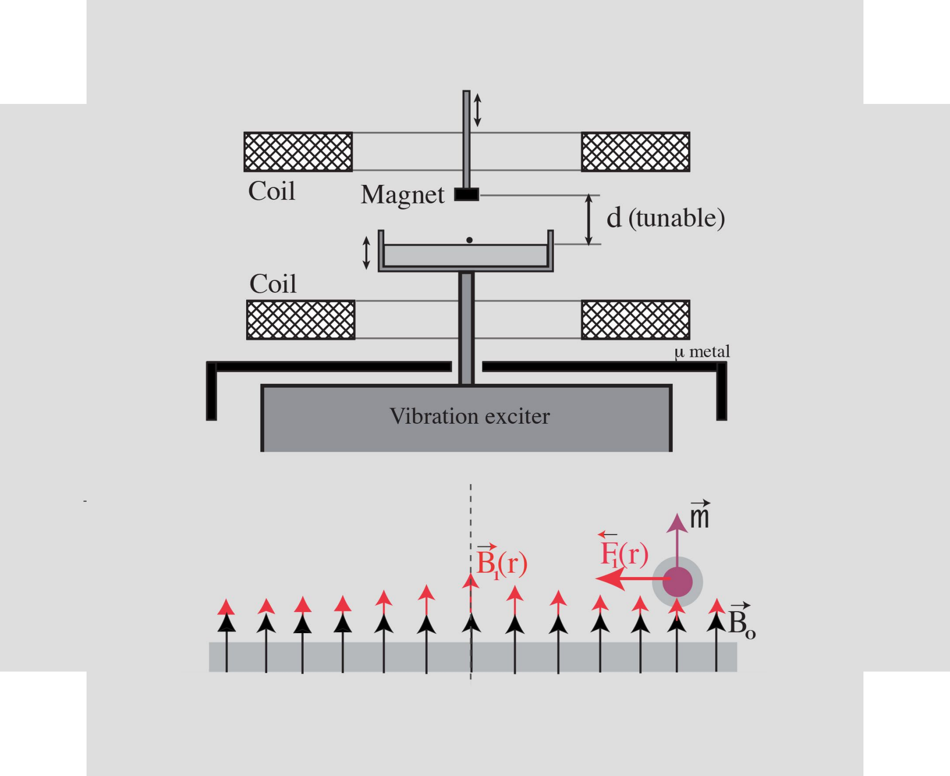
- Pilot wave above the barrier will become evanescent
- Walker's wave is reflected and interfered with older wave, changing the local slope of the pilot wave
- Analogy begins to fail since:
  - Dissipative system
  - Can measure entire trajectory through slits
  - Probability linked to wave amplitude NOT intensity



Couder, Y. Fort. E (13 Oct 2006) Single-Particle Diffraction and Interference at a Macroscopic Scale. *Physics Review Letters*. 97

Quantization of Orbits

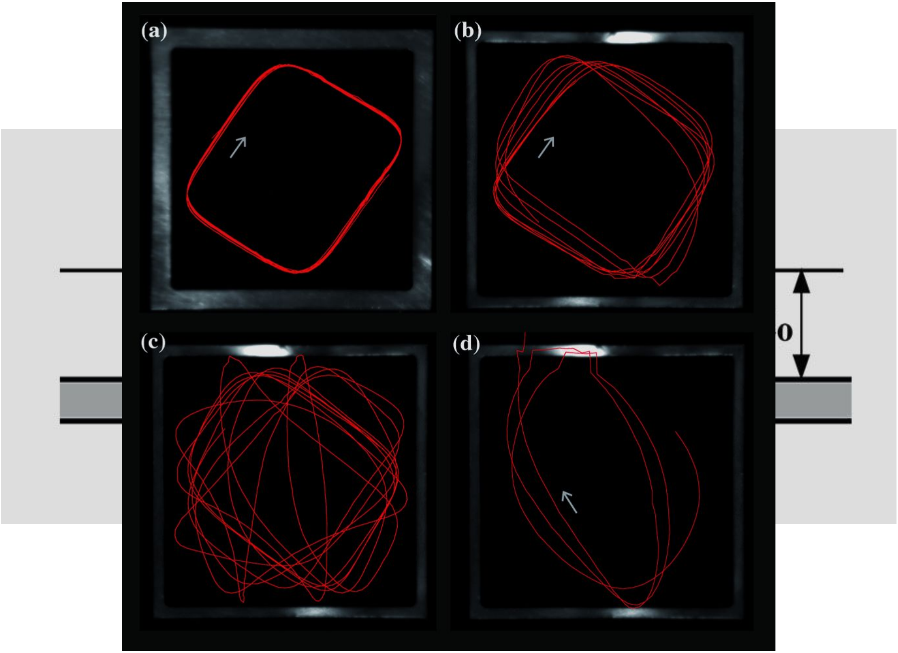
- Complicated experiment needed to observe particle behavior under a center force
- Eigenstates are the closed orbits
  - In high memory systems, observe superpositions of orbits, appears chaotic
  - Observe “wavefunction” collapse after measurement



Labousse, M. Oza, A.U., Perrard, S. Bush, J.W.M. (23 Mar 2016) Pilot-wave dynamics in a harmonic potential: Quantization and stability of circular orbits.Physical Review Letter. 93

Tunneling

- Evanescence of wave over the barrier
  - Wave NOT completely damped over the barrier
- Transmitted wave is analogous to probability current: higher the amplitude of the wave outside the barrier, higher tunneling probability



Eddi, A. Fort, E. Moisy, F. Couder, Y. (16 June 2009). Unpredictable Tunneling of a Classical Wave-Particle Association. Physics Review Letter. 102

Entanglement and Bell’s Inequality

- It is possible to observe Bell Inequality Violations
- Must produce droplets with measurable spin
- Two Assumptions:
  - Locality, expressed in stochastic systems by the Clauser-Horne factorability condition
  - Measurement Independence
- Based on these two assumptions, can develop Bell inequality which can be violated.

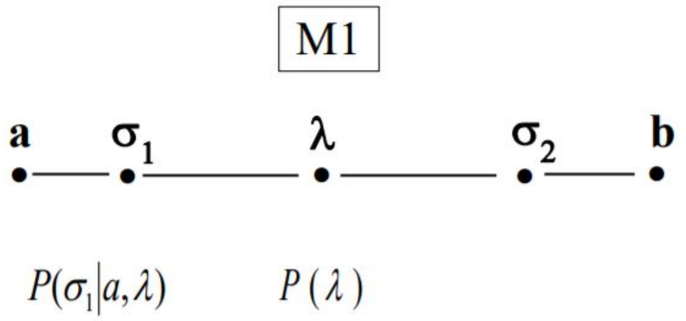


Fig. 1. Correlation graph of Bell’s model M1.
The assumed probabilities are indicated (for the left wing).

References