Imaging and Analysis of Hydrodynamic Quantum Analogs

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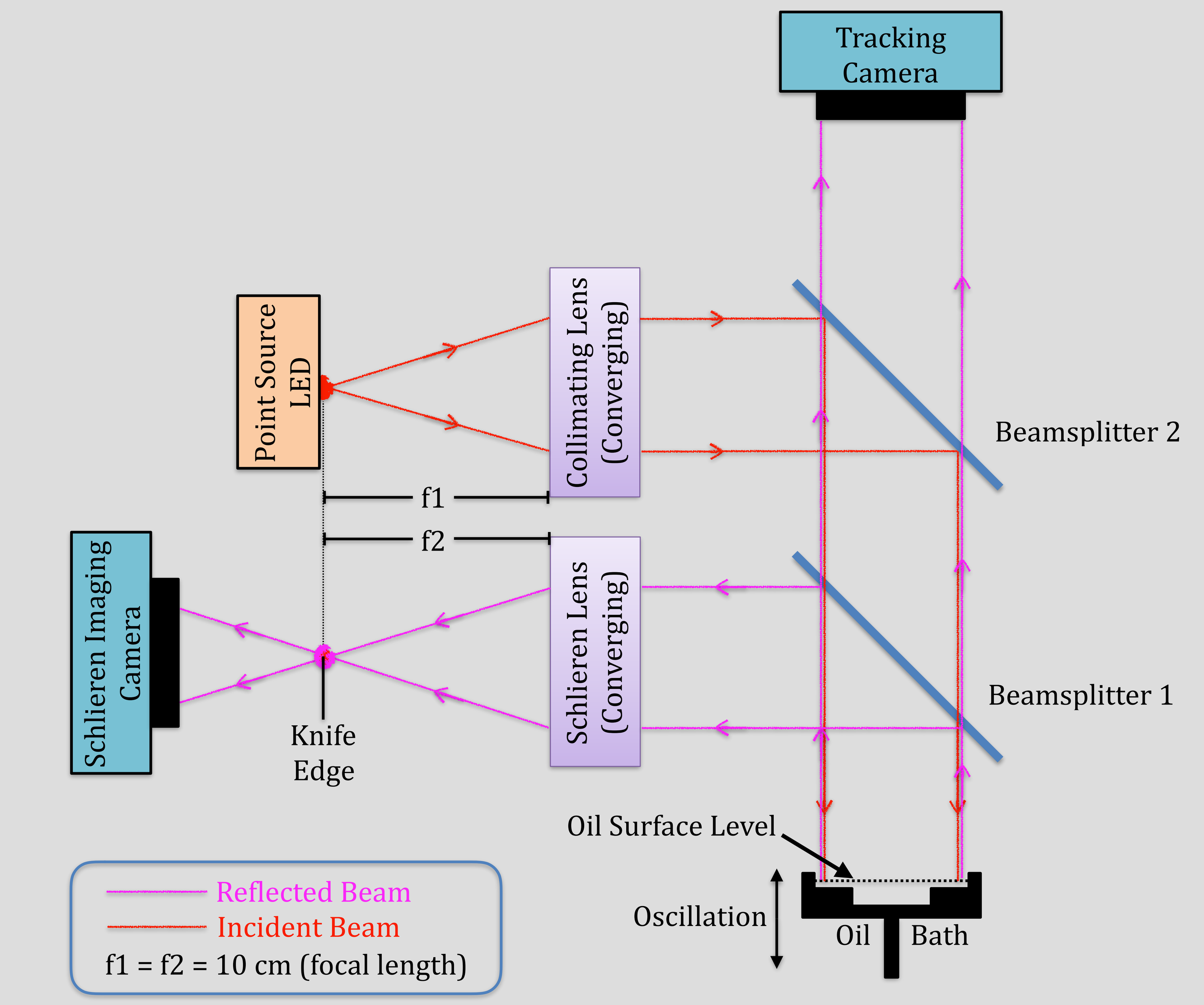
Abstract

Hydrodynamic quantum analogs consist of a small droplet of viscous fluid that is self-propelled across an oscillating bath of the same fluid. Continuous vertical bouncing, and walking horizontal motion, of the droplet can be achieved with careful control over the frequency and amplitude of oscillation. With each rebound, the droplet receives transverse kicks in its motion dependent on the waves of its previous bounces. With variations in bath geometries and subsurface structures, the probability distribution of the droplet's trajectory can be manipulated to induce fascinating behavior. Over short timescales, a droplet will exhibit seemingly random trajectories. However, when the droplet is observed over long timescales, patterns in the cumulative motion of the droplet begin to emerge. The patterns this system maps out over long timescales demonstrate a compelling macroscopic analog to Louis de Broglie's double-solution theory of quantum mechanics.[1] We present the results from various pilot-wave hydrodynamic analog experiments, analysis of which has provided valuable insight into the analogy between a bouncing macroscopic oil droplet and the quantum behavior of microscopic particles.

[1] Louis de Broglie, "Interpretation of quantum mechanics by the double solution theory," Annales de la Fondation Louis de Broglie 12 (4), 399-421 (1987).
[2] Gary S. Settles, Schlieren and Shadowgraph Techniques, (Springer, Berlin, 2001).
[3] Gregory A. Fiete and Eric J. Heller, "Colloquium: Theory of quantum corrals and quantum mirages," Reviews of Modern Physics 75 (3), 933-948 (2003).
[4] Periodic Table of Elements: Chemistry Division, LANL, "Cobalt," 2018 (October 28), (2016).
[5] Albert Einstein, Max Born and Hedwig Born, The Born-Einstein letters: Correspondence between Albert Einstein and Max and Hedwig Born from 1916-1955 with commentaries by Max Born, (Macmillan, London, 1971), p. 158.

We gratefully acknowledge support from the UNC Office of Undergraduate Research, Student Research Fund, and Department of Physics and Astronomy.

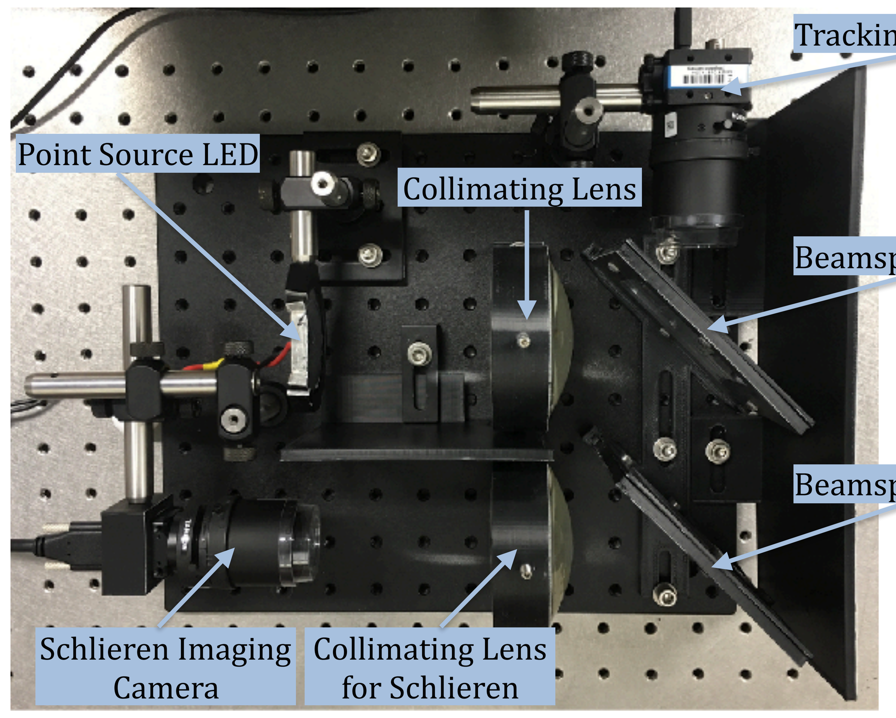
Novel Imaging System

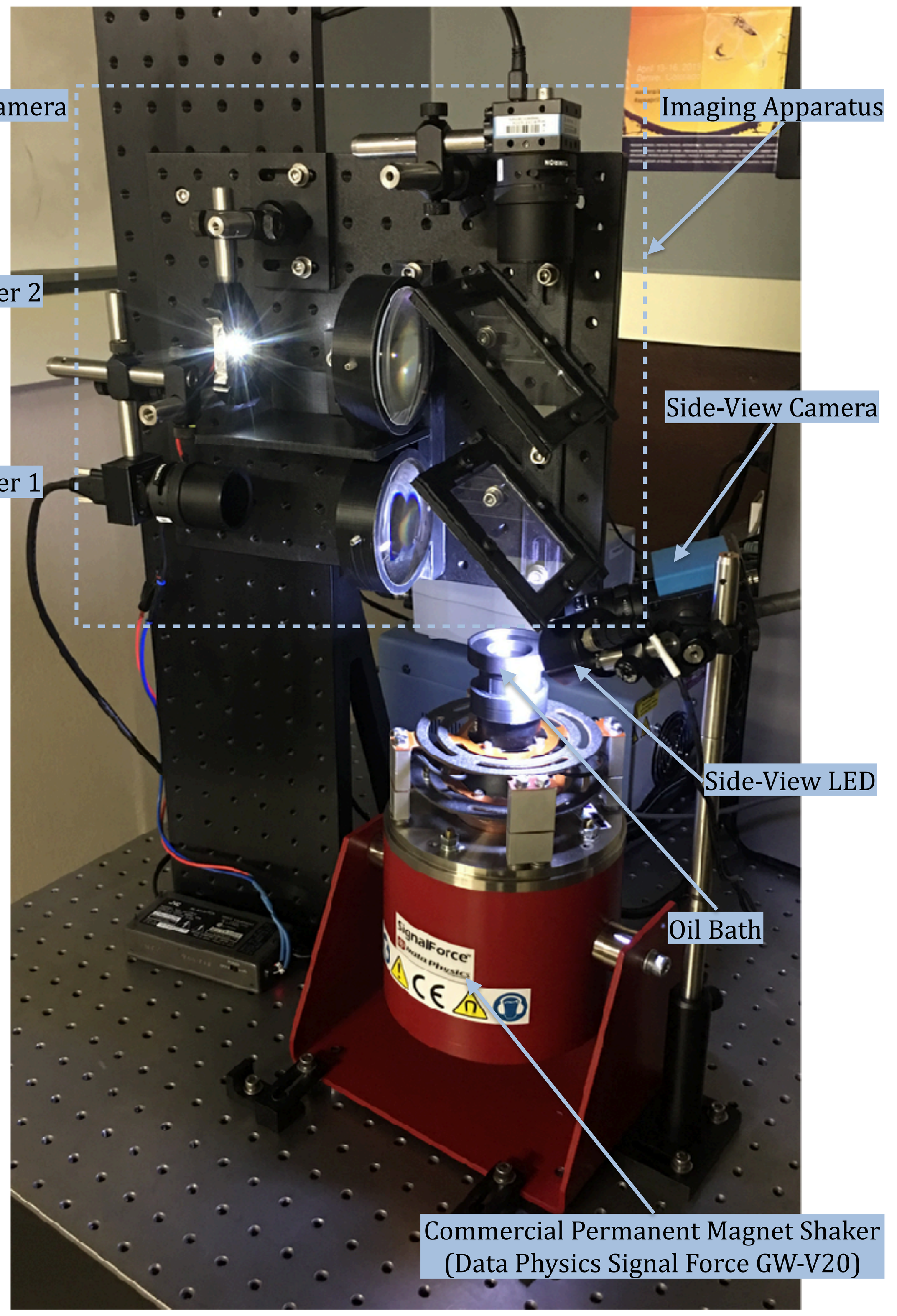


The optical arrangement above allows for the simultaneous observation of the hydrodynamic pilot-wave and the droplet position. This scheme enables the visualization of the short-term chaotic motion of the droplet, the droplet's pilot-wave, as well as the long-term statistical build up of the droplet's trajectory heat-map, helping make direct connections between the pilot-wave and droplet motion across a range of timescales.

Pilot-Wave System

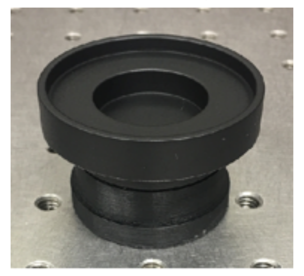
Imaging Apparatus





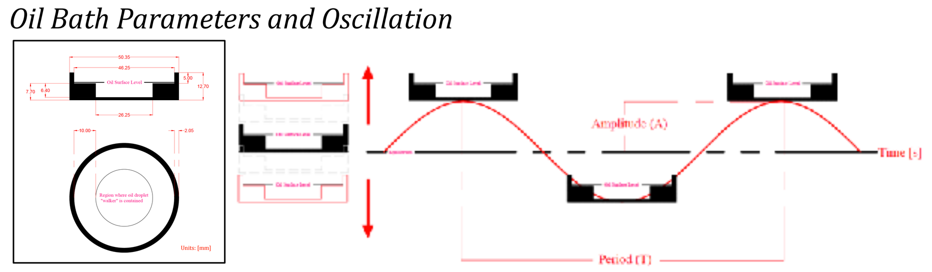
Oil Bath Geometry

Circular Corral (Quantum Corral Analog)



A droplet contained within a circular oil bath (left) produces an axially symmetric statistical wave patterns reminiscent of the full standing wave patterns exhibited by confined surface-state electrons in a quantum corral.[3]

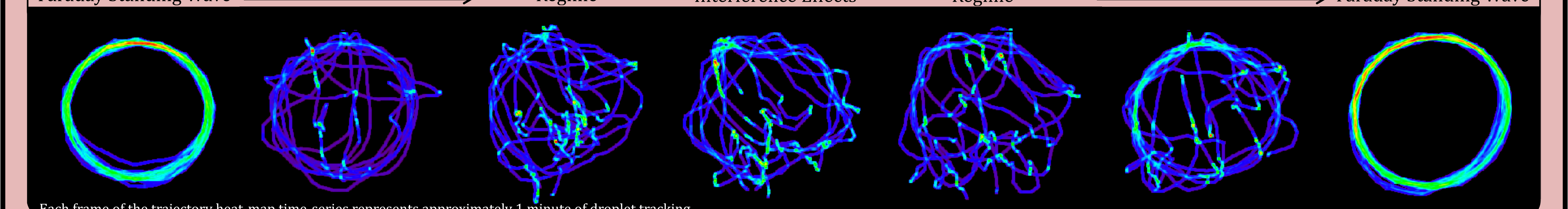
Oil Bath Parameters and Oscillation



Faraday Threshold and the Quantum Corral Analog

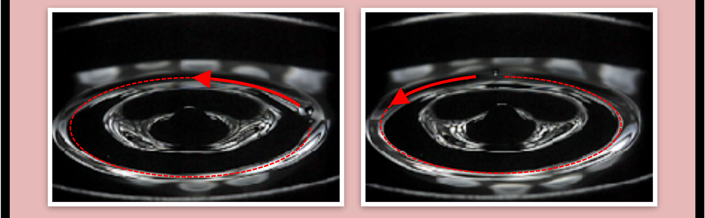
The droplet trajectory heat-map time-series below illustrates the droplet's motion as the oscillator's amplitude of oscillation is varied from an amplitude in excess of the onset of Faraday standing waves to that just below the onset of Faraday standing waves, i.e., the amplitude at which "walking" droplet and interference effects occur, and back again. The long-term probabilistic trajectory of the droplet is directly dependent on the forcing conditions of the bath. The forcing conditions of the bath provide the energy necessary to sustain the bouncing droplet and resulting wave field. Additionally, forcing the bath at the Faraday frequency preconditions the oscillating medium (oil) for a monochromatic wave field.

Start (High Amplitude) Faraday Standing Wave — Decreasing Amplitude → Intermediate Regime — Walking Droplet and Interference Effects — Intermediate Regime — Increasing Amplitude → End (High Amplitude) Faraday Standing Wave



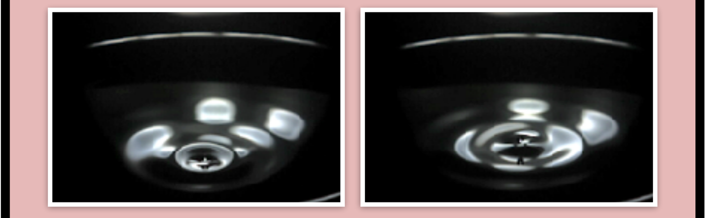
Each frame of the trajectory heat-map time-series represents approximately 1 minute of droplet tracking.

Faraday Standing Waves

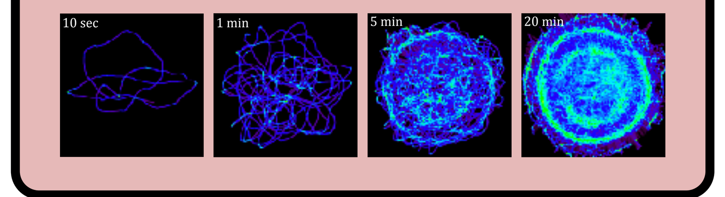


At high oscillation amplitudes, the surface of the oil exhibits significant modulation. By tuning the driving frequency, stable spatial modes can be observed as standing waves. A bouncing droplet in this regime will remain confined within a circular node. The motion is predictable and the pattern generated is the same for all timescales. Frames captured from a side-view video (above) show the circular droplet motion.

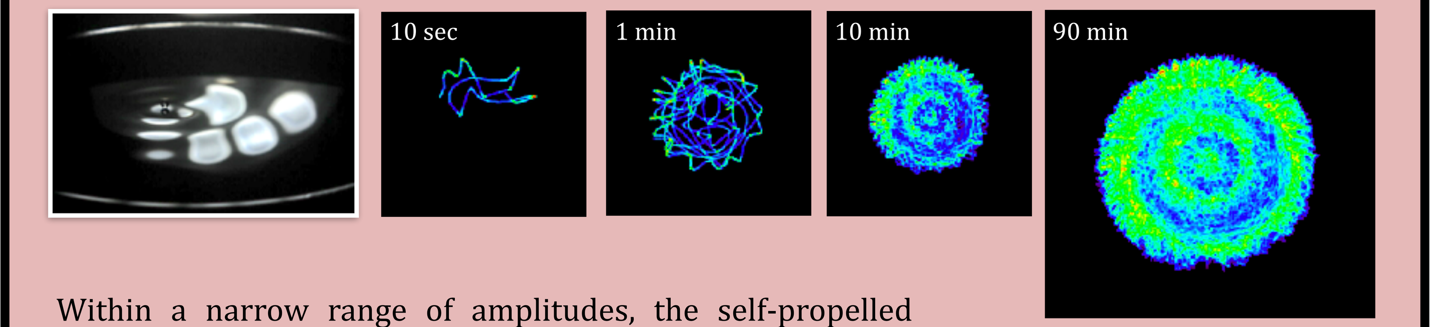
Intermediate Regime



As the oscillation amplitude is reduced, the height of the surface Faraday waves inside the oil bath will decrease until they are barely visible (above). As a result, the waves generated by the droplet bouncing on the oil surface will have a greater impact on its subsequent motion. The patterns generated by the motion of the droplet evolve significantly over time (below).

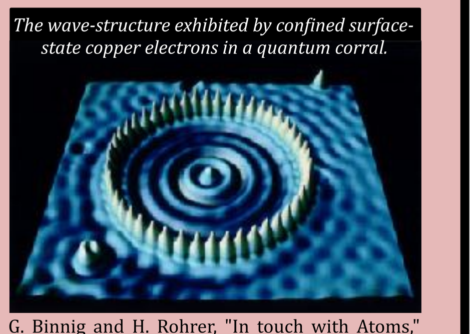


Walking Droplet and Interference Effects



Within a narrow range of amplitudes, the self-propelled droplet (walker) wanders across the oil bath surface under the influence of the generated pilot-wave, i.e., the droplet motion is governed entirely by the waves that the droplet itself creates (above). For short timescales, this motion exhibits apparently random behavior. For long timescales, however, interference patterns emerge that are completely different from the standing Faraday wave patterns. These patterns are due to the interference of the droplet with itself! This behavior is analogous to the standing wave structure exhibited by confined surface-state electrons in a "quantum corral" (right).[3]

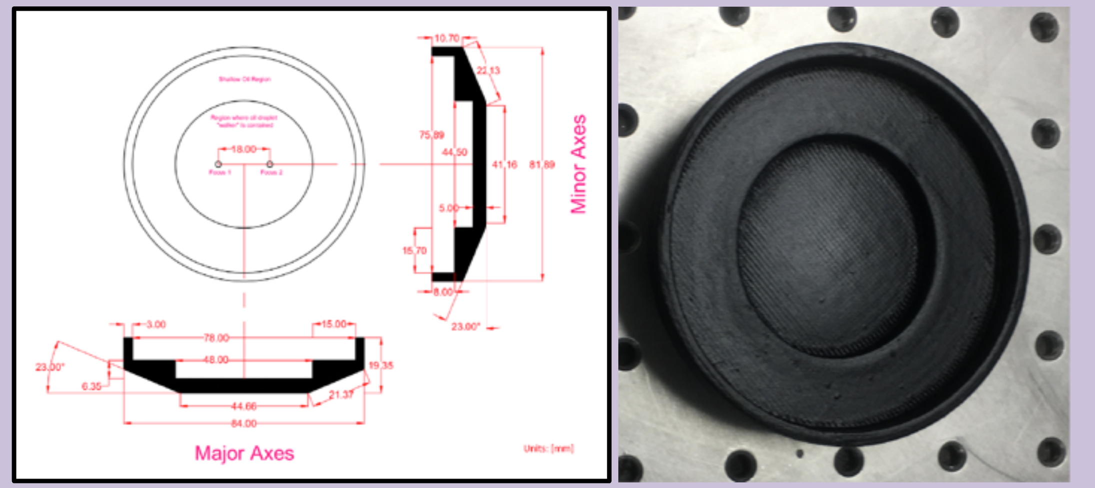
The wave-structure exhibited by confined surface-state copper electrons in a quantum corral.



G. Binnig and H. Rohrer, "In touch with Atoms," Rev. Mod. Phys. 71 (2), S330 (1999).

Further Study

Quantum Mirage



A quantum mirage is the result of any arrangement of adatoms or other defects that produce a buildup of surface-state electron amplitudes at two locations within the coherence length of an electron. In a particular quantum mirage experiment, a single Cobalt (Co) atom produced a spectroscopic mirage in an elliptical corral constructed of magnetic Co atoms on a Cu(111) substrate. The mirage was produced more than 70 Å away.[3] Considering a Cobalt atom is approximately 192 pm, or 1.92 Å, in radius (Van der Waals radius),[4] the projection of the atom's properties across a distance approximately 18 times its diameter to an otherwise empty focus of an elliptical coral geometry is bizarre, to say the least!

In an effort to further probe the analogy between pilot-wave hydrodynamics and quantum mechanics, an elliptical oil bath arrangement modeling the geometry of the quantum mirage (above) has been developed. The elliptical oil bath parameters were determined by correlating an oil droplet diameter of 1 millimeter to the diameter of a Cobalt atom, and extrapolating the remaining parameters. In addition, like the circular corral, the elliptical oil bath was designed to incorporate a shallow region of oil surrounding the portion of the elliptical bath geometry designed to contain the droplet. This shallow region will simulate the leaky walls of a quantum corral and prevent the oil droplet from interacting with the hard barrier surface of the oil bath as it walks across the oscillating oil surface. Furthermore, the depth of the oil in the oil bath will be conducive to standing Faraday waves—based on previous circular corral research.

Quantum Entanglement

Equally bizarre to the quantum mirage, is the theory of quantum entanglement in which entangled quantum systems interact across large distances, famously referred to by Albert Einstein in a personal letter to Max Born as "spooky action at a distance."[5]

An oil bath geometry constructed of two merged circular corral geometries (right) has been developed. This oil bath geometry will be explored with the intent to produce droplet behavior reminiscent of quantum entanglement.