FLUIDS

Quantum physics dropwise

Classical wave-driven particles can mimic basic quantum properties, but how far this parallel extends is yet to be seen. Evidence for quantum-like mirages in a system of droplets moving on a fluid surface pushes the analogy into many-body territory.

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Interference and superposition of particle motion was, until recently, believed to be unique to quantum mechanics. These concepts are useful for describing extended fields — or waves — whose effects can be overlaid at each point in space, but seem incompatible with localized particles following well-defined orbits. This belief was recently shown to be wrong for a class of wave-driven particles via experiments on millimetric silicon droplets bouncing on a silicon bath[1]. Now, writing in *Nature Physics*, Pedro Sáenz and colleagues[2] have shown that a particle in the same system slowly builds up a spatial probability distribution that is closely correlated with the average wave field it excites.

It may seem strange that a fluid drop can actually 'bounce' on a fluid surface without being swallowed by the surrounding fluid. But, in fact, a thin layer of air between the drop and the fluid persists, constantly being renewed if the oscillations are sufficiently fast[3]. When driven violently enough, these drops will start 'walking' across the surface[1].

Curiously, this is closely connected with a discovery made by Michael Faraday in 1831[4]. Forcing a dish containing a thin plane fluid layer into vertical vibrations (for example, using a violin bow), he noticed that sufficiently strong vibrations would cause a pattern of standing waves, which he called crispations, to form on the fluid surface. In other words, a fluid layer subjected to vertical oscillations is intrinsically unstable. If these oscillations are strong enough, the fluid will spontaneously generate standing waves, and just below this threshold the surface will be extremely sensitive. So a bouncing drop can create, if not a big splash, then at least large and long-lived standing surface waves — still without merging with the fluid.

Droplets can even be propelled along the fluid surface by these waves[1]. It is somewhat counterintuitive that standing waves can create motion. It is a bit like moving on caterpillar tracks, sequentially laying down a new segment in order to move forward. A drop that happens, by chance, to bounce — almost touching the surface — at a position slightly displaced from where it took off (emitting its last wave), will bounce on a slightly tilted surface. This imparts a small horizontal momentum to the drop. The next bounce will thus create standing waves centred at a displaced position, and, if the decay time of these waves is sufficiently long, this can lead to sustained horizontal motion.

Fig. 1 | The walking droplet double-slit experiment. The double-slit experiment became emblematic of the interpretation of quantum mechanics through the discussions between Bohr and Einstein in 1927. A 'walking droplet' is seen on its way across the surface of a shallow vibrating layer of silicon oil. The triangular droplet emitter, the barriers and the two rectangular slits can be seen beneath the fluid surface. The walking droplets closely resemble quantum particles driven by a 'pilot wave', but how far the analogy can be taken is presently unknown. Reproduced from ref. [8], APS.

The walking drop depends on its standing wave for its motion and the wave exists only because of the droplet. So the particle and the wave form an inseparable unit akin to the quantum description of particles — in particular, the 'pilot waves' introduced by de Broglie in 1924[5] just prior to the discovery of quantum mechanics and triggering its wave mechanical formulation.

How far can this analogy be taken? As yet, we do not know. One of the first striking observations with walking droplets was spatial discretization. Placing the vibrator and the walking drop on a rotating table produces a system that closely imitates a charged particle circulating magnetic field lines[6]. Indeed, the walker's motion is changed from rectilinear to circular, and, surprisingly, only certain orbits are allowed — just like in the Bohr model of the hydrogen atom. Replacing Planck's constant by the wavelength of the Faraday standing waves multiplied by the mass and velocity of the drop, one gets a sequence of radii matching the Bohr–Sommerfeld quantization rules, the so-called old quantum theory preceding quantum mechanics proper. The full quantum mechanical treatment gives quantized orbits with similar mean radius, but the details are different, because the eigenstates do not correspond to well-defined orbital radii.

To get closer to the heart of quantum mechanics and challenge the statistical 'Copenhagen interpretation', one can use wave-driven particles to imitate individual quantum processes in the hope of obtaining the 'realist' model of quantum mechanics that would have made Einstein and many others so happy. Thus one should be able to describe particles in a superposition of eigenstates, like an entangled pair, or like an electron or a photon passing through the double-slit experiment. Indeed, evidence for 'quantum' interference has already been seen in a droplet version of the double-slit experiment[7], even though one can easily observe through which slit the droplet passes, as part of its wave field can go though the other slit and create interference (Fig. 1). This, however, is not correct: obviously walking droplets can be influenced by their own wave field or that of another droplet, but quantum interference is something very special.

To determine the quantum probability amplitude of going from one point of measurement to another, all paths between them have to be taken into account, each contributing a probability amplitude determined by the classical action for the given path. In the drop experiments that is not the case: the path taken by the particle is singled out and breaks the 'path symmetry'. For the double-slit experiment, the paths through the two slits have a precise phase difference depending on the difference in length between the two paths — something that obviously cannot be maintained in experiment. This asymmetry can be accentuated by putting in a separating wall or a beam splitter before the slits[8], as is typically done in optics experiments[9]. The Schrödinger wave happily splits, but not so for the walking drop.

Another way of imitating basic quantum effects is to go beyond the single particle to probe such intriguing macroscopic quantum states as Bose condensates and superconductivity. In many-body systems, interactions can give rise to complex states as in the Kondo problem, where a localized magnetic impurity radically alters the low-temperature properties of an electron gas.

Saenz et al.[2] have explored this relation, extending earlier work on corrals[10] to show that a localized impurity can strongly affect the superposition of basic states governing the long-term motion of a single particle. This can even lead to 'mirage' effects, projecting from one focal point of the elliptic corral to the other. To go further and imitate features of the spectacular macroscopic quantum states, one needs to look more carefully at systems with many wave-driven particles. One promising result in this direction is the observation of coherent states of many droplets moving in long, narrow channels[11], sharing their wave fields and moving at an elevated velocity. It would be extremely interesting to know how closely such systems can imitate their quantum superconducting analogues. ❐

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