C. HERTLEIN *ET AL.*

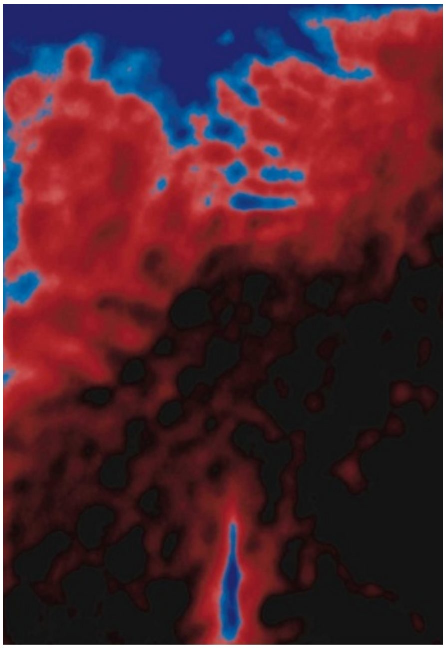

Figure 1 | Critical fluctuations. The demixing of water and the solvent 2,6-lutidine (seen here in false colours), is Hertlein and colleagues' laboratory[1] for measuring the critical Casimir force.

Specifically, they occur when a physical system changes state continuously, for example in a liquid–gas transition, or during the phase separation of a liquid mixture near its 'critical' temperature. Above this critical temperature, the liquid–gas transition does not exist. Close to it, there are large density fluctuations, as if the system were hesitating between two very similar states. Fisher and de Gennes predicted that these fluctuations should also be affected by a confining geometry, just as in the original Casimir effect. If two plates are immersed in a fluid system close to its critical point, a critical Casimir force should arise.

This new force should differ significantly from the original Casimir force in two respects. First, it should depend strongly on temperature, because it is highly sensitive to the distance from the critical temperature. Second, it should be either attractive or repulsive, according to the nature of the two surfaces: if they attract the same component of the liquid mixture, the force should be attractive; if each attracts a different component, the force should be repulsive.

Several groups have tried either to obtain experimental evidence for these astonishing forces or to calculate their effects. Both proved extremely difficult. The first indirect evidence came in 1999, with studies of films of liquid helium on copper plates[3]. Liquid helium has a critical point at very low temperature, where it becomes a superfluid (it starts to flow without friction). Close to this point, the liquid film became thinner, and this phenomenon was successfully analysed by assuming the existence of critical Casimir forces.

Hertlein and colleagues' direct proof[1] comes from measuring the force between two solid objects: a silica plate and, about 0.1 micrometres away, a polystyrene sphere about 3 μm in diameter. Both plate and sphere could be treated such that the expected forces would be either attractive or repulsive. The authors immersed everything in a mixture of water and the organic compound 2,6-lutidine near the mixture's critical point at 307 kelvin (34 °C) (Fig. 1). Their extremely sensitive apparatus used the technique of total internal reflection microscopy to measure the force between the plate and the sphere to an accuracy of 1 femtonewton (10^{-15} N). The size of the Casimir force they found was less than 600 femtonewtons, and its sign could be changed by treating the surfaces differently. A neighbouring group of theorists at the University of Stuttgart in Germany calculated[8] the variation of the effect with temperature and distance; their result is almost exactly the same as that from the experiments.

Is this discovery of any practical importance? As is so often the case, it's too early to tell. But the authors suggest that, as their force can easily be tuned by changing the temperature or by a surface chemical treatment, it could be used to control the aggregation of colloids, a central problem in many areas of materials science. They also note that the original Casimir force turns out to be a problem for attempts to actuate microscale devices: for instance, it makes microcantilevers stick to neighbouring walls. By plunging such devices in a tailored liquid mixture, this mechanical problem could be suppressed by creating repulsive forces. They might well be right in their predictions. Even better, these new forces might find applications that no one has even thought of yet. ■

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QUANTUM MECHANICS

Evolution stopped in its tracks

Lev Vaidman

How do you watch the evolution of something that doesn't evolve? In the classical world, even posing this question would provoke raised eyebrows. But where quantum physics is involved, no question is too silly.

"A watched pot never boils," the saying goes, although the laws of physics tell us that this can't be true. More precisely, the cosy intuitions of classical physics tell us this can't be true. But enter the topsy-turvy realm of quantum physics, and the saying and the science converge. Specifically, a phenomenon known as the quantum Zeno effect states that if we find a system in a particular quantum state, and repeatedly and frequently check whether it is still in that state, it will remain in that state. It does this even if, without constant checking, it would evolve to another state. The watched quantum pot never boils.

Bizarre and abstruse as the whole thing might sound, it could have practical applications, in particular to the field of quantum information[1]. Hence the interest in theoretical studies such as that of De Liberato[2], which appears in *Physical Review A*. De Liberato looks more closely at systems that are subject to the quantum Zeno effect, and finds a procedure that allows us to observe how such systems try to evolve, even though they do not do so. Although Zeno measurements are part of this procedure, they do not stop the evolution. De Liberato instead finds a new, and in this case more powerful, method to hold a quantum system in a given state so that its evolution can still be measured.

But first, some background. The Zeno of the quantum Zeno effect is Zeno of Elea, a Greek philosopher of the fifth century BC from the colonies of southern Italy. In his arrow paradox, he postulated that an instant is indivisible; an arrow, therefore, cannot be in different places at the beginning and the end of an instant. Because, within any instant, the arrow cannot change its place, it can't in fact move at all. Somewhat surprisingly, and despite the development of mathematical tools such as calculus to deal with continuous motion, philosophers are still not sure that classical physics can provide a good answer to Zeno's paradox. What is the nature of the impetus that provides an instantaneous velocity[3]?

Quantum mechanics, oddly enough, has an answer. Its impetus is quantum-mechanical momentum, which is a property of a quantum state at any instant. The velocity of a moving quantum arrow, as represented by its associated quantum wave, can be estimated at any

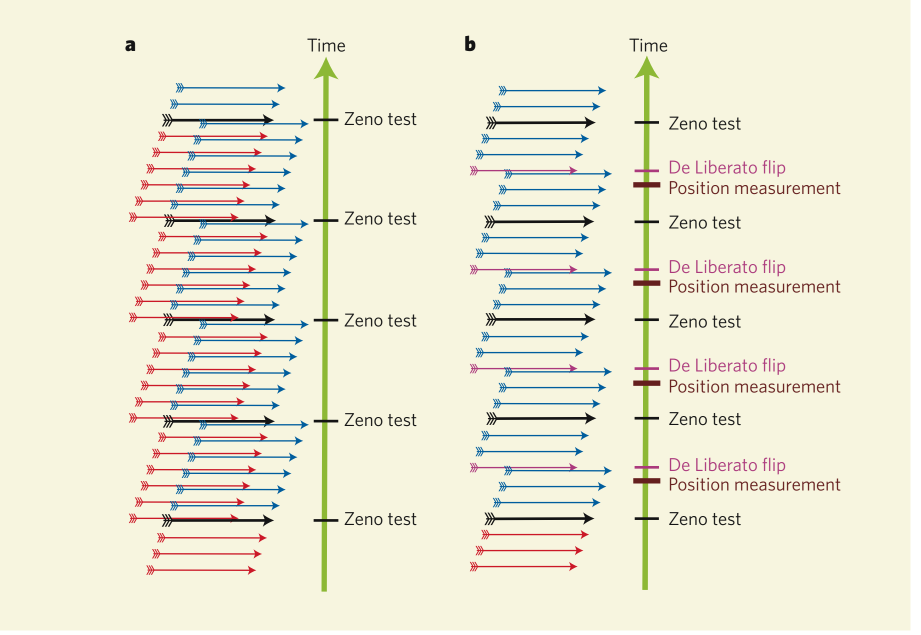

Figure 1 | A step forward, a step back. a, In accordance with the quantum Zeno effect, a quantum arrow with positive momentum (velocity to the right) is brought back to the same position by the frequent measurements made on it. Between these measurements, the arrow is described by two quantum states: one evolving to the future (blue arrows) and another to the past (red). The states are shifted in opposite directions and so a measurement of the arrow's average position will show it to be in the position of the Zeno test, making a measurement of its instantaneous velocity impossible. **b**, De Liberato[2] introduces a different scheme, in which the arrow steps back owing to a quick flip of the relative sign in the superposition of the original and the newly developed state. The future-evolving and past-evolving states are as a result always shifted by the same amount. Just before De Liberato flips, the shift is positive. It is very small relative to the uncertainty in the arrow's position, but (unlike in the scheme in **a**) we can now repeat the procedure many times to resolve the uncertainty and to measure the shift. The instantaneous velocity of the arrow can thus be measured, in spite of the Zeno tests holding the arrow at the origin.

time as its momentum divided by its mass. But although quantum mechanics gets rid of the original paradox, it supplies another unanswered question in the form of the quantum Zeno effect. Why does a quantum arrow stop when we frequently check a localized state of the arrow with non-zero momentum?

The answer is intimately bound up with the Heisenberg uncertainty relation, which states that a quantum system with a definite momentum cannot be exactly localized: its position is uncertain up to the width of its quantum wave. When our arrow moves a distance smaller than this width, its state becomes a superposition of the original quantum state and a new state. A measurement checking whether the arrow is still in the original state might find it there, or might not. The probability that the arrow has moved along is proportional to the square of the time that has elapsed since the last measurement, and becomes very small if the measurements are frequent. Increasing the number of measurements over a given time interval reduces the probability gradually to zero — the quantum Zeno effect kicks in.

Let's look more closely at the example of our arrow, which has a non-zero momentum and is initially localized at the origin. We perform very frequent Zeno measurements of the quantum state to check that the arrow is maintaining this momentum and that it returns to its localized state at each measurement. But between these Zeno measurements, one might think, the arrow can move a little to the right, in the direction of its momentum. Between these measurements, its average position will be shifted in proportion to its velocity, and this will allow its velocity to be measured.

This conclusion is in fact incorrect. Between two measurements, a quantum system is described by two quantum states: one evolving towards the future, defined by the first measurement, and one evolving towards the past, defined by the second measurement[4] (Fig. 1a). The first state is shifted to the right, and the second to the left; thus measuring the average position of the arrow between full Zeno measurements yields no shift.

The shift does not vanish, however, if the position measurements are made shortly before each Zeno measurement. Indeed, at this point, while the past-evolving state is near the origin, the future-evolving state is almost at its maximum shift. Thus, the arrow has a net shift to the right. For the Zeno effect to work, this shift has to be much smaller than the uncertainty in the arrow's position. Very many position measurements are needed to detect this tiny shift. If we continue the procedure long enough to get enough position measurements, then at some point a Zeno test is likely to fail. If the Zeno measurements are more frequent, they will take longer to fail, and more position measurements can be made; but in this case the shift to be measured becomes smaller, meaning that even more measurements are needed to detect it. The conclusion is that there is no way to measure the position shift, and thus the instantaneous velocity, of a system held by Zeno measurements.

But this is not so, as De Liberato[2] shows. His procedure (Fig. 1b) uses one device that performs two tasks: it holds the arrow, and it performs a position measurement on it. In each gap between Zeno tests, when the original state evolves into a superposition of the original state and a new state, De Liberato proposes a quick interaction to flip the relative signs of these states half-way between two tests. This change of sign shifts the arrow back to the left. At the time of the next Zeno test, the arrow is where it was originally, and the test succeeds with certainty. If the external conditions do not change, De Liberato's repeated sign flips will hold the arrow at the origin for ever — even if we do not perform Zeno tests between the flips.

De Liberato's position measurement comes just before the sign flip, at the time when the displacement is maximal. The state evolving into the past from the Zeno tests is just the time-reverse of the state evolving into the future, so at this point, both states are maximally displaced. The number of times we can repeat the procedure is not limited as before: the Zeno tests will not fail because of the motion of the arrow. The only possible reason for their failure is the disturbance of the state owing to position measurements. But this possibility is discounted by the so-called protective measurement regime[5], in which the coupling of the position measurement is weak and the state is protected from changes by the Zeno tests. We can measure the velocity of an arrow held at the origin.

Paradoxes have always been a driving force for understanding nature. Quantum mechanics, probably more than any other theory, is full of paradoxes[6]. Quantum mechanics helps to resolve Zeno's arrow paradox but leads to the quantum Zeno effect, which seems in itself inherently paradoxical. Work such as that of De Liberato[2] shows us that we have not yet uncovered all such secrets of quantum mechanics, which is now almost a century old. That is becoming increasingly relevant as technology transforms yesterday's quantum thought experiments into today's laboratory demonstrations, and even into practical devices. ■

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