The quantum measurement problem

LOTTE MERTENS is a PhD candidate at the Institute of Physics (UvA) and IFW Dresden. She received the Lorentz Graduation Award for Theoretical Physics 2020 and UvA Thesis Prize 2021 for her Master's thesis, described here.

→ Reference

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[2] L. Mertens, M. Wesseling, N. Vercauteren, A. Corrales-Salazar and J. van Wezel. *Phys. Rev.* A 104, 052224 (2021). doi: 10.1103/PhysRevA.104.052224

→ If you are a fan of science-fiction movies, you might have noticed an interesting pattern. From the celebrated 'Interstellar' to most Marvel movies, when directors want to explain some impossible phenomenon, they tend to just put the word 'quantum' in front of it to make it seem plausible. This might just be because they are fascinated by quantum mechanics, but I think it is the pop-culture manifestation of questions that arise in the scientific community, based on the fact that quantum mechanics might be the best tested but least understood physics theory that exists at the moment.

Quantum mechanics is the theory that describes the smallest objects in the world around us, from single atoms to small dust particles. This microscopic world behaves remarkably differently from our 'classical' everyday experience, even though the macroscopic objects around us are made of the same quantum particles. For example, a chair will never be in two places at the same time, but a quantum object might, in the form of a superposition (see also page 22 of issue 12 of Amsterdam Science). The fact that superpositions exist has been proven experimentally, as single particles and even large organic molecules have been shown to interact with their superposed partners – something known as quantum interference. However, any individual measurement of a quantum state will give a single, classical outcome: a particle is observed here or there, but never in both places simultaneously. Given a quantum state, we can predict how likely each outcome is (using the so-called Born rule, postulated in 1926) but what exactly happens to the state upon measurement is a mystery. The inability to describe the transition from a quantum superposition to a classical state is called the quantum measurement problem.

There are many ideas on how to solve this problem; which ones are correct, if any, remains a matter of lively debate. As experiments probing the world of quantum mechanics are becoming ever more advanced, involving ever larger quantum mechanical objects, we are getting closer to the invisible line between quantum and classical behaviour. Now is the time to take stock of the possible solutions to the measurement problem, and see how they hold up when applied to experimental settings that will soon be realised in the lab.

> **"A particle is observed here or there, but never in both places simultaneously"**

One common belief is that whenever a quantum superposition collapses upon measurement, there are parallel universes in which all other allowed measurement outcomes are realised. Unfortunately, this 'many worlds' interpretation of quantum measurement cannot be verified experimentally, since we can never reach these alternate realities (unlike what Marvel would have you believe). An alternative idea is that the 'collapse' of a quantum superposition to a classical state is a real, physical process. This means it takes some (short) amount of time, and has other features that we should be able to measure experimentally. Mathematical models describing how this process might work are called objective collapse models.

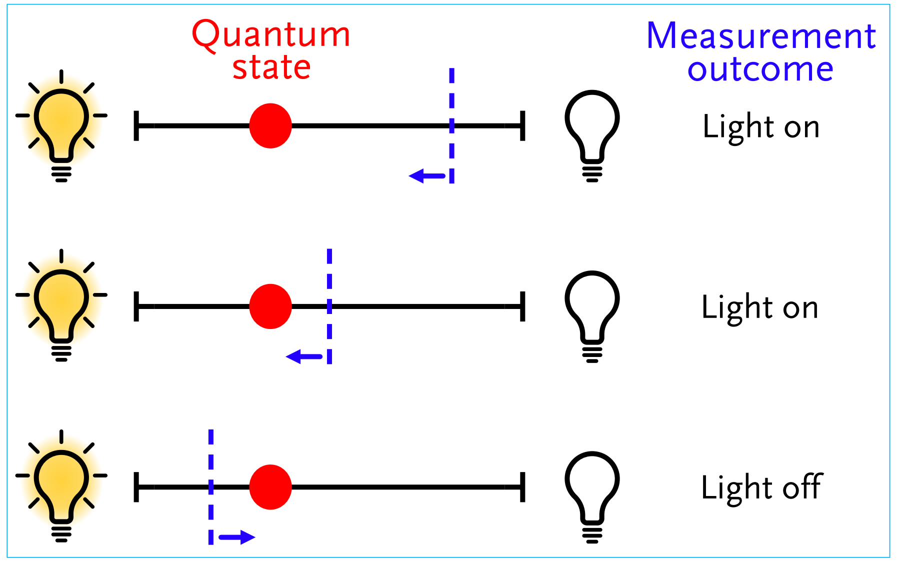
Importantly, we found that if objective collapse occurs, this process must have two key characteristics: non-unitarity and non-linearity. A non-unitary process does not conserve energy; a special and possibly worrisome feature. However, this happens on such a small scale that it would not influence our everyday experience. Non-linearity can be explained with an example of sound waves. The speed of sound is equal for any wave in the same medium, independent of the properties of the wave itself: the waves propagate linearly. A non-linear sound wave would, in theory, have a velocity that depends on a property of the wave itself. This means that a loud scream might travel faster than a whisper. Of course, this does not happen with real sound waves, but imagine how we would perceive music if sound waves were non-linear!

Some existing objective collapse models are not non-unitary and non-linear, which means we can immediately rule them out. We wanted to construct our own model, which naturally reproduces the frequencies of different measurement outcomes as observed in laboratories, without imposing it as an axiom. To do this, we considered the simplest possible quantum system, which only has two possible measurement outcomes. Imagine, for example, a lamp being on or off. A quantum lamp could be in a superposition between being 40% on and 60% off, in a way that, according to Born's rule, if you measure a hundred times you will find that the light is on approximately forty times.

We constructed an equation describing the time evolution of a two-state system during measurement. How this equation works can be visualised on a line, as seen in the Figure. The red point on the line is the initial quantum state of the system, which is in superposition. The endpoints of the line are the two possible measurement outcomes: light on (left) and light off (right). Depending on the position of the red dot compared to the blue dashed line, the system will collapse (during measurement) to the left or the right. For each measurement, the position of the blue dashed line lies at a completely random position. Consequently, the measurement outcomes follow Born's rule.

> **"Getting closer to the invisible line between quantum and classical behaviour"**

To connect the mathematics to the physics involved, we also considered a magnetic system to show that one can derive the right behaviour for a more realistic physical system. However, this is only a proof of principle, and there are unanswered questions. For example, how do we extend our results to more general systems? More research is needed to give a definite answer to the main question: could this be the solution to the quantum measurement problem? Ω



← Figure
The measurement outcomes of a 'quantum lamp'. The red dot is the initial superposed state of the system. The endpoints of the line are the two possible measurement outcomes: light on (left) and light off (right). For each measurement, the blue dashed line lies at a random position and determines the outcome, as indicated by the blue arrows.