Exploring quantum systems that don't find equilibrium

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Not only quantum systems, but also large objects such as the spiral galaxy NGC 1300 can adopt a meta-stable state that leads to surprising effects. Credit: Hubble Heritage Team, ESA, NASA

Some physical systems, especially in the quantum world, do not reach a stable equilibrium even after a long time. An ETH researcher has now found an elegant explanation for this phenomenon.

If you put a bottle of beer in a big bathtub full of ice-cold water, it won't be long before you can enjoy a cold beer. Physicists discovered how this works more than a hundred years ago. Heat exchange takes place through the glass bottle until equilibrium is reached.

However, there are other systems, especially quantum systems, that don't find equilibrium. They resemble a hypothetical beer bottle in a bath of ice-cold water that doesn't always and inevitably cool to the temperature of the bath water, but rather reaches different states depending on its own initial temperature. Until now, such systems have puzzled physicists. But Nicolò Defenu, a postdoc at the ETH Zurich Institute for Theoretical Physics, has now found a way to elegantly explain this behavior.

A more distant influence

Specifically, we are talking about systems in which the individual building blocks influence not only their immediate neighbors, but also objects further away. One example would be a galaxy: the gravitational forces of the individual stars and planetary systems act not only on the neighboring celestial bodies, but far beyond that—albeit ever more weakly—on the other components of the galaxy.

Defenu's approach begins by simplifying the problem to a world with a single dimension. In it, there is a single quantum particle that can reside only in very specific locations along a line. This world resembles a board game like Ludo, where a little token hops from square to square. Suppose there is a game die whose sides are all marked 'one' or 'minus one', and suppose the player rolls the die over and over again in succession. The token will hop to a neighboring square, and from there it will either hop back or else on to the next square. And so on.

The question is, What happens if the player rolls the die an infinite number of times? If there are only a few squares in the game, the token will return to its starting point every now and then. However, it is impossible to predict exactly where it will be at any given time because the throws of the die are unknown.

Back to square one

It's a similar situation with particles that are subject to the laws of quantum mechanics: there's no way to know exactly where they are at any given time. However, it is possible to establish their whereabouts using probability distributions. Each distribution results from a different superposition of the probabilities for the individual locations and corresponds to a particular energy state of the particle. It turns out that the number of stable energy states coincides with the number of degrees of freedom of the system and thus corresponds exactly to the number of allowed locations. The important point is that all the stable probability distributions are non-zero at the starting point. So at some point, the token returns to its starting square.

The more squares there are, the less often the token will return to its starting point; eventually, with an infinite number of possible squares, it will never return. For the quantum particle, this means there are an infinite number of ways in which the probabilities of the individual locations can be combined to form distributions. Thus, it can no longer occupy only certain discrete energy states, but all possible ones in a continuous spectrum.

None of this is new knowledge. There are, however, variants of the game or physical systems where the die can also contain numbers larger than one and smaller than minus one, i.e. the steps allowed per move can be larger—to be precise, even infinitely large. This fundamentally changes the situation, as Defenu has now been able to show: in these systems, the energy spectrum always remains discrete, even when there are infinite squares. This means that from time to time, the particle will return to its starting point.

Peculiar phenomena

This new theory explains what scientists have already observed many times in experiments: systems in which long-range interactions occur do not reach a stable equilibrium, but rather a meta-stable state in which they always return to their initial position. In the case of galaxies, this is one reason they develop spiral arms rather than being uniform clouds. The density of stars is higher inside these arms than outside.

An example of quantum systems that can be described with Defenu's theory are ions, which are charged atoms trapped in electric fields. Using such ion traps to build quantum computers is currently one of the largest research projects worldwide. However, for these computers to really deliver a step change in terms of computational power, they will need a very large number of simultaneously trapped ions—and that is exactly the point at which the new theory becomes interesting. "In systems with a hundred or more ions, you would see peculiar effects that we can now explain," says Defenu, who is a member of ETH Professor Gian Michele Graf's group. His colleagues in experimental physics are getting closer every day to the goal of being able to realize such formations. And once they've got there, it might be worth their while to have a cold beer with Defenu.

More information: Nicolò Defenu, Metastability and discrete spectrum of long-range systems, *Proceedings of the National Academy of Sciences* (2021). DOI: 10.1073/pnas.2101785118

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