Spooky action put to order: Physicists classify different types of 'entanglement'

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A property known as "entanglement" is a fundamental characteristic of quantum mechanics. Physicists and mathematicians at ETH Zurich show now how different forms of this phenomenon can be efficiently and systematically classified into categories. The method should help to fully exploit the potential of novel quantum technologies.

"I think I can safely say that nobody understands quantum mechanics." Thus spoke the American physicist Richard Feynman—underlining that even leading scientists struggle to develop an intuitive feeling for quantum mechanics. One reason for this is that quantum phenomena often have no counterpart in classical physics. A typical example is the quantum entanglement: Entangled particles seem to directly influence one another, no matter how widely separated they are. It looks as if the particles can 'communicate' with one another across arbitrary distances. Albert Einstein, famously, called this seemingly paradoxical behaviour "spooky action at a distance."

When more than two particles are entangled, the mutual influence between them can come in different forms. These different manifestations of the entanglement phenomenon are not fully understood, and so far there exists no general method to systematically group entangled states into categories. Reporting in the journal *Science*, a group of mathematicians and physicists around Matthias Christandl, professor at the Institute for Theoretical Physics, provides an important contribution towards putting the "spooky action" to order. The team has developed a method that allows them to assigning a given quantum state to a class of possible entanglement states. Such a method is important because, among other things, it helps to predict how potentially useful the quantum state can be in technological applications.

Putting entangled states in their place

Together with Brent Doran, a professor in the Department for Mathematics at ETH Zurich, and David Gross, a professor at the University of Freiburg in Germany, Christandl and his PhD student Michael Walter, first author of the *Science* publication, introduce a method in which different classes of entangled states are associated with geometric objects known as polytopes. These objects represent the "space" that is available to the states of a particular entanglement class. Whether or not a given state belongs to a specific polytope can be determined by making a number of measurements on the individual particles. Importantly, there is no need to measure several particles simultaneously, as is necessary in other methods. The possibility to characterise entangled states through measurements on individual particles makes the new approach efficient, and means also that it can be extended to systems with several particles.

The ability to gain information about entangled states of several particles is a central aspect of this work, explains Christandl: "For three particles, there are two fundamentally different types of entanglement, one of which is generally considered more 'useful' than the other. For four particles, there is already an infinite number of ways to entangle the particles. And with every additional particle, the complexity of this situation gets even more complex." This quickly growing degree of complexity explains why, despite a large number of works that have been written on entangled states, only very few systems with more than a handful of particles have been fully characterized. "Our method of entanglement polytopes helps to tame this complexity by classifying the states into finitely many families," adds Michael Walter.

Quantum technologies on the horizon

Quantum systems with several particles are of interest because they could take an important role in future technologies. In recent years, scientists have proposed, and partly implemented, a wide variety of applications that use quantum-mechanical properties to do things that are outright impossible in the framework of classical physics. These applications range from the tap-proof transmission of messages, to efficient algorithms for solving computational problems, to tech-niques that improve the resolution of photolithographic methods. In these applications, entangled states are an essential resource, precisely because they embody a fundamental quantum-mechanical phenomenon with no counterpart in classical physics. When suitably used, these complex states can open up avenues to novel applications.

A perfect match

The link between quantum mechanical states and geometric shapes has something to offer not only to physicists, but also to mathematicians. According to Doran, the mathematical methods that have been developed for this project may be exploited in other areas of mathematics and physics, but also in theoretical computer science. "It usually makes pure mathematicians a bit uncomfortable if someone with an 'applied' problem wants to hit it with fancy mathematical machinery, because the fit of theory to problem is rarely good," says Doran. "Here it is perfect. The potential for long-term mutually beneficial feedback between pure mathematicians and quantum information theory and experiment is quite substantial."

The method of entanglement polytopes, however, is more than just an elegant mathematical construct. The researchers have shown in their calculations that the technique should work reliably under realistic experimental conditions, signalling that the new method can be used directly in those systems in which the novel quantum technologies are to be implemented. And such practical applications might eventually help to gain a better understand of quantum mechanics.

More information: Walter M, Doran B, Gross D, Christandl M: Entanglement Polytopes: Multi-Particle Entanglement from single-particle information. *Science*, 2013.

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