A non-probabilistic quantum theory produces unpredictable results

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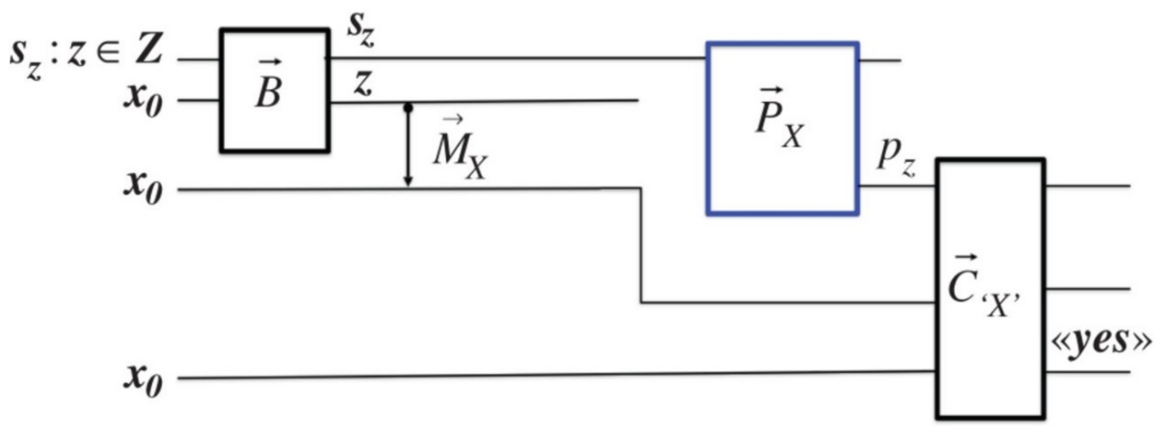

A scheme in superinformation theory. The new study shows that this deterministic theory exhibits unpredictability as a consequence of the impossibility of cloning certain states. Credit: C. Marletto. ©2016 Proceedings of The Royal Society A

(Phys.org)—Quantum measurements are often inherently unpredictable, yet the usual way in which quantum theory accounts for unpredictability has long been viewed as somewhat unsatisfactory. In a new study, University of Oxford physicist Chiara Marletto has developed an alternative way to account for the unpredictability observed in quantum measurements by using the recently proposed theory of superinformation—a theory that is inherently non-probabilistic. The new perspective may lead to new possibilities in the search for a successor to quantum theory.

Accounting for unpredictability

The unpredictability observed in quantum experiments is one of the unique features of the quantum world that sets it apart from classical physics. One prominent example of quantum unpredictability is the double-slit experiment: When sending a stream of particles (such as photons or electrons) through two small slits in a plate, the individual particles are detected at different locations on a screen behind the plate. Although it's possible to predict the probability of a particle impacting at a certain location, it's not possible to predict specifically where any individual particle will end up.

Traditionally, this apparent probabilistic behavior that is observed in experiments has been accounted for in quantum theory by using the Born rule. In 1926, the German physicist Max Born developed this rule to determine the probability of finding a quantum object at a certain location—or more generally, the probability that any measurement on a quantum system will produce a particular observed outcome, depending on the quantum state of the object.

The Born rule is a unique part of quantum theory in that it is the only stochastic, or randomly determined, element in quantum theory. The Born rule has basically been added by fiat on top of a theory that is otherwise deterministic. Ever since the rule was first proposed, physicists have questioned the probabilistic nature of quantum theory with the Born rule, and have wondered whether it would still be possible to account for observations, including unpredictability, without this rule.

In general, quantum theory without the Born rule would be completely non-probabilistic. The main problem with the proposal for such a theory, called "unitary quantum theory," is that it does not appear, at first sight, to agree with the observations of unpredictability in quantum measurements. One attempt to reconcile this conflict is the so-called "decision-theoretic approach," which was recently proposed by David Deutsch and established by David Wallace, and which forms the basis for the arguments in the new study.

"The decision-theoretic approach shows that a rational agent that knows unitary quantum theory only (but does not assume the Born rule) would have the same expectations, in the experimental situations where the Born rule applies, as if he had assumed the Born rule," Marletto explained. "This is a remarkable result, but has been contested on the grounds that it relies on axioms of rationality that seem subjective and not physically motivated."

Deterministic quantum theory

In the new paper, Marletto builds on the decision-theoretic approach to show that a completely deterministic quantum theory can essentially function as if it were probabilistic, so that measurements would be expected to produce unpredictable results, like those in the double-slit experiment and many others.

"There are two things: one, my work shows that unpredictability can arise under deterministic theories, and that it is a direct consequence of the impossibility of cloning certain sets of states," Marletto told *Phys.org*. "That unpredictability can arise under deterministic theories may seem a little surprising at first. But the point is that 'unpredictability' just means that it is impossible to build a predictor—a machine that would reliably predict the outcome of a single measurement of given observable on a system prepared in a given state. This impossibility is just like that of the no-cloning theorem, and does not require any probabilistic structure. Probabilities, instead, come into play only when considering patterns occurring in repeated experiments.

"Two, this work updates and generalizes the decision-theory approach to the Born rule in quantum theory, which was proposed to reconcile deterministic unitary quantum theory without the Born rule with the appearance of stochasticity in quantum experiments. In particular, it shows that most of the assumptions of that approach are not, as previously thought, subjective decision-theoretic axioms, but follow from physical properties of superinformation theories. It also establishes under what conditions superinformation theories support that argument, thereby defining a class of theoretical possibilities in which the successor of quantum theory might be sought."

Overall, the new results show that, to explain quantum experiments that have perplexed physicists for decades—experiments in which repeated, identical measurements produce different outcomes, where individual outcomes are unpredictable and appear to be random–it is not necessary to appeal to the Born rule or any other probabilistic assumptions.

Possibilities and impossibilities

As Marletto explains in her paper, her work builds on recent research in which she and Deutsch, also at Oxford, reformulated quantum theory as a type of superinformation theory under a new framework that they call the constructor theory of information.

When Deutsch and Marletto originally proposed the constructor theory of information a couple of years ago, they were searching for a way to link classical and quantum information under the same general framework. In the end, what they developed was a set of principles that can be thought of as part of the foundations from which all the laws of physics emerge—essentially, a new fundamental theory of physics.

The basic principle of constructor theory is that every law of physics must be expressible as a statement about which physical transformations (or tasks) are possible and which are impossible, and why. An example of a possible information processing task under quantum theory is switching any state to any other state, and vice versa. An example of an impossible task is cloning, which is creating an identical copy of an unknown state.

Constructor theory does not specify any particular laws of physics, but instead its principles are intended to supplement and underlie all laws of physics, both the known and currently unknown laws. This is similar to the way in which fundamental principles, such as conservation of energy and mass, must be obeyed by all laws of physics. Specific laws can be formulated to predict what will actually happen (not just what is possible) in specific circumstances. For example, some laws predict the trajectory of a projectile, others predict the flow of water, or the path of electricity, etc., always with the constraint of complying to constructor theory's principles. These restraints also provide a potential way to test the theory.

"The main way to test constructor theory is to test the theories conforming to its principles—for instance, the interoperability principle for information," Marletto said. "So, the same as one would do to test the principle of conservation of energy. In regard to the class of superinformation theories, they might be used to design new experiments about quantum theory, by providing a space of new theoretical possibilities where a rival of quantum theory may be sought. The promising feature is that, unlike most existing proposals for frameworks to generalize quantum theory, superinformation theories are deterministic and local."

In the future, Marletto plans to work on further developing the constructor theory framework, along with the superinformation theories it supports.

"Superinformation theories allow one to unify classical and quantum information under the same framework," she said. "There are exciting prospects about understanding what other superinformation theories there are in addition to quantum theory; coming up with measures of entanglement or quantum coherence in this generalized scenario would have the advantage of being more general than current quantum-information-theoretic ones. Another line of research that appears very interesting is to merge the theory of superinformation with the newly proposed constructor theory of thermodynamics, which will have bearings on the current quantum thermodynamics enterprise. There is also a project that Deutsch and I would like to pursue, that is to understand how superinformation theories can support the notion of 'relative state,' which is crucial in unitary quantum theory."

More information: Chiara Marletto. "Constructor theory of probability." *Proceedings of The Royal Society A*. DOI: 10.1098/rspa.2015.0883. Also at arXiv:1507.03287 [quant-ph]