Experimental refutation of a class of quantum epistemic models

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What is the fundamental nature of the quantum state? Is it ontic or epistemic? Or, in other words: does it correspond to a real property of the physical system or does it represent our knowledge about the system? These long-asked questions have seen recent theoretical breakthroughs: no-go theorems show that epistemic models reproducing the results of quantum theory are highly contrived – e.g., discontinuous. We present a simple optical experiment – based on modulated weak coherent states – allowing the experimental verification of one of these no-go theorems, therefore refuting a large class of quantum epistemic models.

Introduction

Quantum theory assigns to every physical system a given *quantum state* $|\psi\rangle$. Such a procedure has been well known for decades. However, there is still no definite answer to the following question: what is the fundamental nature of the quantum state? Let us indeed suppose that our present description of Nature is incomplete: the *real state* λ of a physical system is not known. Then, we have two alternatives.

First, the *ontic* (from Greek "ontos", real) alternative: the quantum state is a real property of the system. In this case, there is a one-to-one correspondence between λ and $|\psi\rangle$: reality corresponds to the quantum state $|\psi\rangle$ possibly complemented by some "hidden variables" that are still not known. Different quantum states $|\psi_1\rangle \neq |\psi_2\rangle$ correspond to different real states $\lambda_1 \neq \lambda_2$.

Second, the *epistemic* (from Greek "episteme", knowledge) alternative: the quantum state is *not* a real property of the system and reflects only our incomplete knowledge of the system – like statistical distributions in classical physics. There are indeed some reasons to doubt of the reality of the quantum state: this mathematical object cannot be measured directly and exhibits counter-intuitive phenomena, such as the measurement postulate and wave-function collapse, which would find a convincing explanation in such a model. With this hypothesis, different quantum states $|\psi_1\rangle \neq |\psi_2\rangle$ can correspond to the same underlying reality $\lambda_1 = \lambda_2$.

The above alternatives, illustrated in figure 1, have been formulated with precision in [1]. In [2], Pusey, Barrett, and Rudolph (PBR) have theoretically shown that these alternatives can be tested experimentally: epistemic models cannot reproduce all the predictions of quantum theory if they satisfy the property, termed *preparation independence*, that independently prepared pure quantum states correspond to product distributions over ontic states. An experiment based on the PBR theorem has been carried on with trapped ions and reported in [3].

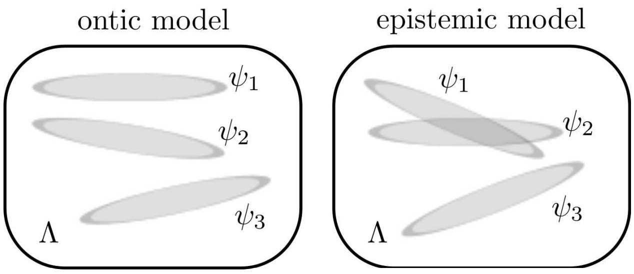

Figure 1: Illustrative distinction between ontic and epistemic models. Depicted are the support of probability distribution $P(\lambda|Q_k)$ for preparation Q_k of a physical system associated with distinct pure quantum states ψ_k, $k = 1,2,3$, in the space Λ of real states λ of the system. In an ontic model (left) distinct quantum states give rise to probability distributions with no overlap, while in an epistemic model (right) distinct quantum states may correspond to the same reality, as ψ_1 and ψ_2 in the figure.

The PBR paper has generated a certain "buzz": several studies inspired by this result have flourished, and we will not list them here. We will focus on the result demonstrated by Patra, Pironio, and Massar (PPM) in [4]. They have shown that epistemic models cannot reproduce all the predictions of quantum theory if they satisfy another constraint, a natural property of continuity. The advantage of this no-go theorem is that it allows an experimental test already at the level of a single system, contrary to the PBR argument. We have carried on such an experimental test, reported in [5], by using modulated weak coherent states of light.

In the following, we first present the PPM no-go theorem and outline its demonstration, since it is used for the experimental test. Then, we describe the quantum optics experiment allowing to test the predictions of quantum mechanics. Finally, we summarize the experimental results we have obtained, and conclude on the reality of the quantum state.

Theorem

We start with the definition of what we call δ-continuous epistemic models. Let $\delta > 0$ and let B^{δ}_{ψ} be the ball of radius δ centered on $|\psi\rangle$, i.e., B^{δ}_{ψ} is the set of states $|\phi\rangle$ such that $|\langle\phi|\psi\rangle| \geq 1-\delta$. We consider the preparation procedure Q of a physical system, associated with the probability distribution $P(\lambda|Q)$ over real states λ. We say that a model is δ continuous if for any preparation Q, there exists a state λ such that for all preparations Q' corresponding to quantum states $\phi_{Q'}$ in the ball $B^{\delta}_{\psi_Q}$ centered on the state $|\psi_Q\rangle$, we have $P(\lambda|Q') > 0$.

The PPM no-go theorem states that if an epistemic model were to reproduce the predictions of quantum mechanics, then there is a fundamental constraint on its δ continuity. The theorem is as follows: δ-continuous epistemic models with $\delta \geq 1-\sqrt{(d-1)/d}$ cannot reproduce all the measurement statistics of quantum states in a Hilbert space of dimension d.

To prove the theorem, we consider d preparations Q_k, $k = 1,\ldots,d$, corresponding to distinct quantum states $|\psi_k\rangle$ all contained in a ball of radius δ, and a measurement M that yields one of d possible outcomes $r = 1,\ldots,d$. If preparation Q_k is followed by measurement M, we denote by $P(r|M,Q_k)$ the probability of outcome r.

By definition of a δ-continuous epistemic model, it makes the prediction

$$\sum_k P(k|M,Q_k) = \sum_k \sum_\lambda P(k|M,\lambda)P(\lambda|Q_k) \geq \sum_\lambda \min_k P(\lambda|Q_k) \equiv \varepsilon > 0\,. \qquad (1)$$

However, this is in contradiction with quantum theory. Indeed, let $\{|j\rangle : j = 1,\dots,d\}$ be a basis of the Hilbert space. The d distinct states $|\psi_k\rangle = \frac{1}{\sqrt{d-1}}\sum_{j\neq k}|j\rangle$ are all at mutual distance $\delta = 1-|\langle\psi_k|\psi\rangle| = 1-\sqrt{(d-1)/d}$ from the state $|\psi\rangle = \frac{1}{\sqrt{d}}\sum_j |j\rangle$. If M is the measurement in the basis $\{|j\rangle\}$, then $P(k|M,Q_k) = 0$ for all k, in contradiction with (1).

Experiment

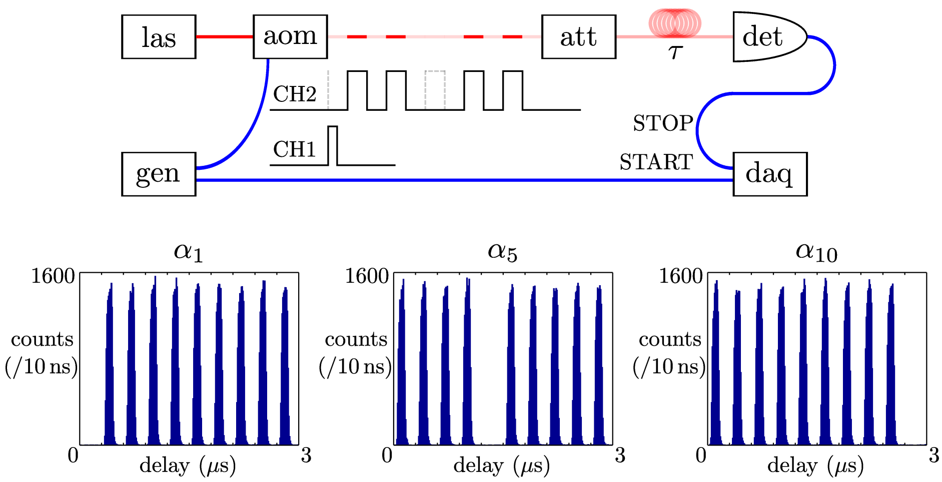

Figure 2: Quantum optics experiment allowing to test the distinct predictions of quantum theory and δ-continuous epistemic models. The light of a long-coherence-time continuous laser (las) in the telecommunication C-band is cut into $d = 3$, 10, 30, 50 or 80 pulses of 100 ns width, with one missing, by an acousto-optic modulator (aom) driven by a pattern generator (gen). The produced coherent states $|\alpha_k\rangle$, with mean photon number $\alpha^2 = 0.2$ after a strong attenuation (att) brings them to the single-photon level, are good approximations of the states $|\psi_k\rangle = \frac{1}{\sqrt{d-1}}\sum_{j\neq k}|j\rangle$, where $\{|j\rangle\}$ denotes a time basis. These states are stored during a time τ in a fiber loop before detection by a superconducting single-photon detector (det). A data acquisition system (daq) registers each detection time relative to the time at which the state preparation began. It thus allows the experimental evaluation of $\varepsilon = \sum_k P(k|M,Q_k)$. In the bottom of the figure are shown the measurement results in the case $d = 10$ for $k = 1,5,10$.

Our experimental setup is depicted and commented in figure 2. The proof of the PPM no-go theorem is at the heart of the experiment, which aims to product states $|\psi_k\rangle = \frac{1}{\sqrt{d-1}}\sum_{j\neq k}|j\rangle$, $j,k = 1,\dots,d$, in a Hilbert space of dimension d, measure them in the basis $\{|j\rangle\}$, and evaluate the quantity $\varepsilon = \sum_k P(k|M,Q_k)$. This is realized with modulated weak coherent states of light cut into time bins.

Results

Our experimental results are summarized in table 1.

d	3	10	30	50	80
δ	0.184	0.051	0.017	0.010	0.006
$\varepsilon_{\mathrm{m}} \times 10^3$	0.26	0.45	1.27	1.62	1.66
$\Delta\varepsilon_{\mathrm{m}} \times 10^3$	± 0.05	± 0.07	± 0.18	± 0.23	± 0.28
$\varepsilon_{\mathrm{p}} \times 10^3$	0.24	0.41	0.99	1.58	2.46
$\Delta\varepsilon_{\mathrm{p}} \times 10^3$	± 0.09	± 0.15	± 0.37	± 0.58	± 0.88

Table 1: Experimental results. Parameters d are the investigated dimensions of the quantum state space, with the corresponding values of $\delta = 1 - \sqrt{(d-1)/d}$. Measured values ε_{m} are given with their statistical uncertainty $\Delta\varepsilon_{\mathrm{m}}$. Values ε_{p} correspond to quantum theory predictions when taking into account experimental imperfections, with approximate uncertainty $\Delta\varepsilon_{\mathrm{p}}$ arising from uncertainty on instrument parameters.

Experimentally, the measured values of ε are non-zero and seem therefore in conflict with quantum theory prediction $\varepsilon = 0$. Nevertheless, our experiment suffers from known imperfections, namely loss, limited detection efficiency, detector dark counts and finite extinction ratio of the modulator. When taking into account these imperfections, our measurements are in agreement with quantum theory predictions, see table 1.
Though because of experimental imperfections all continuous epistemic models cannot be ruled out by our experiment, we can refute a large class of epistemic models, the ones for which $\varepsilon > \varepsilon_m(\delta)$, with ε describing how epistemic the model is, and δ how continuous it is. It shows that, in order to reproduce the predictions of quantum theory, an epistemic model has to be highly discontinuous.
Finally, we note that such a claim can be made only by drawing careful assumptions on the experiment and its interpretation. A more complete discussion and a somewhat tempered conclusion are realized in [5].

Conclusion

In summary, building on recent theoretical breakthroughs, we have experimentally tested the fundamental nature of the quantum state. Our results are in agreement with the predictions of quantum mechanics, and therefore demonstrate – under certain assumptions – the reality of the quantum state.
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References

[1] N. Harrigan and R. W. Spekkens, ”Einstein, Incompleteness, and the Epistemic View of Quantum States”, Foundations of Physics **40**, 125 (2010).

[2] M. F. Pusey, J. Barrett, and T. Rudolph, ”On the reality of the quantum state”, Nature Physics **8**, 475 (2012).

[3] D. Nigg, T. Monz, P. Schindler, E. A. Martinez, M. Chwalla, M. Hennrich, R. Blatt, M. F. Pusey, T. Rudolph, and J. Barrett, ”Can different quantum state vectors correspond to the same physical state? An experimental test”, http://arxiv.org/abs/1211.0942 (2012).

[4] M. K. Patra, S. Pironio, and S. Massar, ”No-Go Theorems for ψ-Epistemic Models Based on a Continuity Assumption”, Physical Review Letters **111**, 090402 (2013).

[5] M. K. Patra, L. Olislager, F. Duport, J. Safioui, S. Pironio, and S. Massar, ”Experimental refutation of a class of ψ-epistemic models”, Physical Review A **88**, 032112 (2013).