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Progress in Physics (52)

Seeing quantum superpositions

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Introduction

In quantum theory, a single particle — a photon for example — can occupy two spatial positions simultaneously. Surprisingly, this superposition principle is supposed to hold at any scale as quantum theory makes no distinction between small and large systems. To better account for what we observe in our daily experiences where classical behaviors readily emerge, theorists and experimentalists have been working hand in hand for decades to probe the limits of the superposition principle.

Nowadays, decoherence is widely accepted as one of the fundamental problems limiting the ability of macroscopic systems to maintain quantum features. As the size of a quantum system increases, it increasingly interacts with its surroundings, rapidly losing its quantum properties. Several experiments, such as the use of Rydberg atoms for probing the electromagnetic field of a high-finesse cavity [M. Brune et al. PRL 77, 4887 (1996)] or the use of a trapped ion interacting with engineered reservoirs [C. Monroe et al. Science 272, 1131 (1996)], are beautiful illustrations of this idea.

However, even if a macroscopic system is sufficiently decoupled from the environment, its quantum features remain difficult to observe. In particular, the observation of its quantum nature requires extremely precise measurements [see e.g. N. Mermin, Phys. Rev. D 22, 356 (1980) or more recently P. Sekatski et al. Phys. Rev. Lett. 113, 090403 (2014)]. This naturally raises the question of whether the human eye — with its many imperfections — can see quantum superpositions. It might be that quantum theory applies at any scale but the eye cannot reveal it, i.e. provides an erroneous classical description of the physical reality that is quantum even at macroscopic scales.

Method description

The response of the human eye to light pulses with various intensities has already been studied [F. Rieke and D. A. Baylor, Rev. Mod. Phys. 70, 1027 (1998)]. In particular, in the few photon regime, experimental results indicate that at a wavelength of 500 nm, human vision can be modeled by a threshold detector preceded by loss, i.e. a detector with a threshold at 7 photons with an efficiency of 8%. This means that about two hundred photons in average need to be sent into the eye to get a high enough excitation in the brain to consciously see light.

One may then wonder whether there is a practical way to create quantum superposition states with a sufficiently large photon number so that its quantum nature can be detected with the eye. The task is a priori challenging. Since current technologies can only produce superpositions with small photon numbers, one may use many independent quantum superpositions, each made with a few photon numbers. Although certain collective measurements of these independent superpositions can reveal their quantum nature [N. Brunner et al. Phys. Rev. A 78, 052110 (2008)], the realistic model of the eye that is described before cannot. Another example is the proposal presented in [P. Sekatski et al. Phys. Rev. Lett. 103, 113601 (2009)] where single photons are amplified through a cloning operation. It has been shown that the resulting superpositions could be revealed with human-eye based detectors in this scenario only if very strong assumptions are made on the source. For example, it is necessary to assume that the source produces true single photons which can be entirely described in a basis made with two states only [E. Pomarico et al. New J. Phys. 13, 063031 (2011)].

Together with Valentina Caprara Vivoli, a PhD student in the Group of Applied Physics at Geneva, and Dr. Pavel Sekatski, a senior postdoc in the Institute for Theoretical Physics in Innsbruck, we go beyond state of the art methods by making a concrete yet simple proposal for experimentally testing the capability of the human eye to see quantum superpositions. The principle of our proposal is shown in Fig. 1.

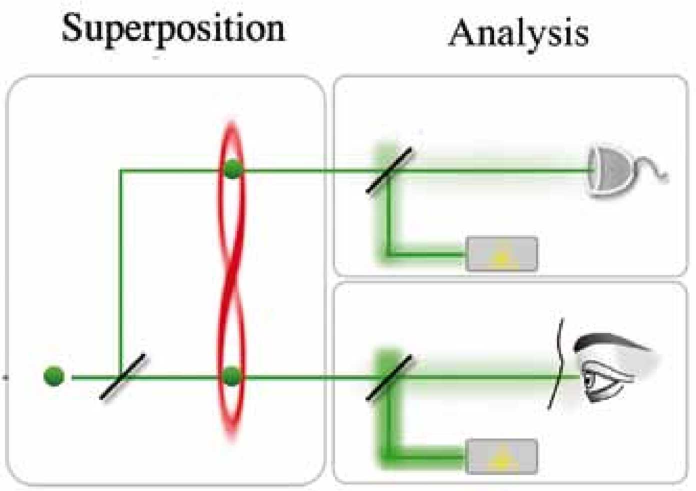

Fig. 1. Principle of the proposal to test the capability of the human eye to observe quantum superpositions. The superposition is created by sending a single photon into a balanced 50/50 beamsplitter. The reflected mode is analyzed by a standard photon detector while an eye based detection is used for the transmitted mode. Both detections are preceded by an unbalanced beamsplitter that is used to combine the mode that is analyzed with laser light. Using laser lights with appropriate intensities and with various phases, we can prove that the photon is in a quantum superposition of being transmitted and reflected by the first beamsplitter.

It starts with a single photon that is sent into a beamsplitter — a kind of partially reflecting mirror which transmits only half of the light. Due to its quantum nature, the photon occupies both the transmitted and reflected modes after the beamsplitter, i.e. it is in a quantum superposition of two different spatial modes. Physicists write that the state after the beamsplitter is

$$|\psi_-\rangle = \frac{1}{\sqrt{2}}(|1\rangle_t|0\rangle_r - |0\rangle_t|1\rangle_r)$$

where $|1\rangle_t$ means one photon in the transmitted mode for example. To verify this, the transmitted part is sent into an eye whereas the reflected mode is analyzed by a standard photon detector. The latter clicks if at least one photon occupies the reflected mode, i.e. is a detector with a threshold at 1 photon. Without additional elements, the single photon detector would click half of the experimental runs while the eye would never see light. This cannot prove that the photon is a quantum superposition, since a completely classical scenario in which a single photon is produced half of the runs and systematically sent into the photon detector would lead to the same detection events.

The trick for proving that the single photon is in a quantum superposition state is to combine both the reflected and transmitted modes with laser light into unbalanced beamsplitters, see Fig. 1. Thank to an interference at the beamsplitter, the superpositions with opposite phases

$$\frac{1}{\sqrt{2}}(|1\rangle + |0\rangle) \text{ and } \frac{1}{\sqrt{2}}(|1\rangle - |0\rangle)$$

become distinguishable, i.e. they lead to two different probability distributions in photon number. As an example, we see in Fig. 2 that for a laser intensity such that 100 photons of the laser light are reflected in average, the probability distributions can be well distinguished with a threshold detector that would only click if the photon number is larger than 100. This means that we can distinguish the superposition states

$$\frac{1}{\sqrt{2}}(|0\rangle \pm |1\rangle)$$

with any threshold detector by controlling the laser intensity to adapt the number of reflected photons to the threshold of the detector.

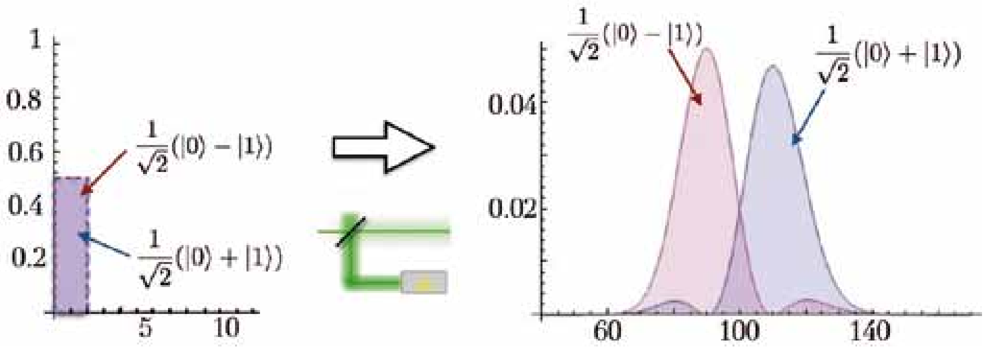

Fig. 2. The figure on the left shows the probability of finding n photons when measuring the photon number in the superposition states

$$\frac{1}{\sqrt{2}}(|0\rangle \pm |1\rangle)$$

In both cases, we can find 0 photon and 1 photon only, with equal probabilities. The figure on the right shows the probability of finding n photons when the previous superposition states are combined into a beamsplitter along with laser light so that 100 laser photons in average are reflected. The two probability distributions are now distinguishable: When their photon number is measured, one of them more often shows photons numbers smaller than 100 while the other one mostly indicates photon numbers larger than 100. This is due to an interference effect at the beamsplitter in which most of the laser photons are reflected or transmitted depending on the phase of the superposition states.

What we have proposed is to adjust the intensity of the upper laser in Fig. 1 so that 1 photon in average is added to the mode reflected by the first beamsplitter. When the photon detector clicks, this essentially projects the state of the transmitted mode into

$$\frac{1}{\sqrt{2}}(|0\rangle_t - |1\rangle_t)$$

i.e. is not seen by the eye even when the corresponding laser is tuned to the right intensity. Similarly, when the detector does not click, the transmitted mode is projected in

$$\frac{1}{\sqrt{2}}(|0\rangle_t + |1\rangle_t)$$

which can be seen by the eye upgraded by appropriate laser intensity. By changing the phase of both lasers, we can prove that the photon after the first beamsplitter is coherently delocalized between the reflected and transmitted modes, i.e. the photon is in a quantum superposition. Crucially, this can be shown without assumption on the photon number in each mode nor on the way the state has been created.

Outlook

A detailed feasibility study in which the photon is created by a currently available source and taking into account the loss along the way from the source to the detectors as well as the detector/eye efficiencies, has confirmed that quantum superpositions can be revealed in the setup of Fig. 1 with present day technologies. Such an experiment would be the first one where the human eye is used to reveal the quantum nature of photonic states. From a practical point of view, such an experiment would show that a very coarse grained detector — here the eye — can be upgraded by laser light up to the point where it becomes useful for quantum experiments. It would be interesting to show that this simple technique can be applied to any detector, including noisy detectors, such as the widely available cameras in our smartphones. Anyway it is safe to say that probing human vision with quantum light is a *terra incognita*. This makes it an attractive challenge on its own.

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