Conditional visibility and its connection to weak measurement

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One of the quintessential features of quantum mechanics is embodied by the duality principle, which forbids the coexistence of wave and particle behaviours. In this work, we demonstrate how a small interaction between two quantum systems makes it possible to perform biased sampling that can lead to apparent violation of the duality principle and behaviour similar to weak amplification.

The duality principle is one of the building blocks of quantum science. It provides us with one of the most well-known statements about quantum mechanics: the presence of interference and the existence of which-alternative information are mutually exclusive. Greenberger and Yasin considered a two-alternative system (a qubit), and after defining a quantitative measure of which-alternative information (the predictability \( P \)) and a quantitative measure of interference (the visibility \( V \)), they demonstrated the result \( V^2 + P^2 = 1 \).

Englert studied the more formal situation of a qubit embedded in an environment, where interaction with other quantum systems is possible [1], and where Greenberger and Yasin’s result is generalized to the inequality

\[ V^2 + P^2 \leq 1. \]  

The significance of the duality principle is in the fact that the involved quantities bound each other: the more is known about the alternatives, the less they can interfere and vice versa. This principle has been put to the test many times in many different regimes [2]. In all of the experimental tests, the duality principle always prevailed. In a recent experiment, Menzel et al. reported high which-alternative information and high visibility fringes in a single experiment [3]. They used pairs of photons entangled in position and momentum generated though spontaneous parametric down-conversion (SPDC) with a type II nonlinear crystal and a Hermite-Gaussian pump mode.

In our work, we exploit the presence of two degrees of freedom in a single physical system, to model both a qubit and the environment. To keep the treatment simple, and without losing any power in our arguments, we consider an environment which is also a qubit. A convenient way of realizing this situation in an optics framework is by exploiting the polarization and two eigenmodes of orbital angular momentum of value \( +\ell \) and \( -\ell \). The fact that we have a pair of two-alternative systems at hand makes it possible to lift the distinction between main system and environment, albeit \( V \) and \( P \) will have to consistently refer to one of them. We will see that interesting results will follow from the symmetry of the two roles.

We find an analogy between conditional visibility measurements and weak measurement due to a symmetry of the measurement procedures: the roles of system and environment are interchanged in the two cases. In the case of conditional visibility, a measurement on the system is performed after successful selection of a state of the environment, while in the case of weak measurement, a measurement on the environment (usually called “pointer”) is performed after successful selection of a state of the system [4, 5]. The analogy of these two procedures, together with the symmetry between system and environment, indicates that one can formulate our experimental findings within the framework of weak measurement. This result provides insight into the nature of weak measurement and is consistent with the recent notion that weak values are present in all von Neumann measurement schemes [6].