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## Wheeler's delayed-choice thought experiment: Experimental realization and theoretical analysis

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### Abstract

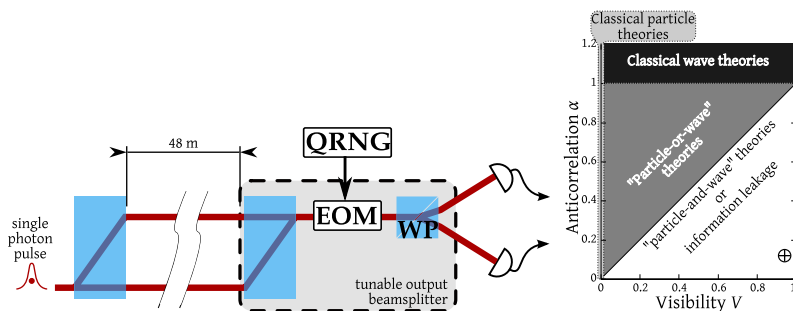
Wheeler has strikingly illustrated the wave-particle duality by the delayed-choice thought experiment, in which the configuration of a 2-path interferometer is chosen after a single-photon light-pulsed has entered it. We present a quantitative theoretical analysis of an experimental realization of Wheeler's proposal.

### 1 INTRODUCTION

Wheeler has strikingly illustrated the wave-particle duality when he proposed the delayed-choice thought-experiment, where the output beamsplitter of a Mach-Zehnder interferometer (MZI) is inserted or removed after a single-photon light-pulse has entered it [1]. Since the wave-like or particle-like behavior of the light-pulse can be shown with these complementary experimental setups, this wave-particle duality seems consistent with a light choosing to be a wave or a particle, according to the experimental setup. Wheeler's delayed-choice experiment challenges such a naive interpretation by delaying the experimental setup choice, so that the light-pulse can only "learn" this choice after having entered the setup.

### 2 EXPERIMENTAL REALIZATION

We recently realized almost ideally this thought experiment [2]. The light pulses are true single-photons, emitted by a NV<sup>-</sup> color center in a diamond nanocrystal [3]. The photon number of the pulse is checked by observing an anticorrelation parameter  $\alpha = 12\% < 1$  on the output ports of a beamsplitter [4].



**Figure 1.** *Left: sketch of the experimental setup. Right: possible theories compatible with the parameters  $V$  and  $\alpha$ .  $\oplus$  corresponds to the experimental results.*

As shown in figure 1, we have built a Jamin polarization interferometer, followed by an electro-optical modulator (EOM) and a Wollaston prism (WP). This interferometer is equivalent to a MZI where the output beamsplitter reflection coefficient can be tuned from  $1/2$  (closed configuration) to  $0$  (open configuration) in  $40$  ns. The two paths of this interferometer are spatially separated by  $5$  mm and propagate over  $48$  m, which corresponds to a propagation time of  $160$  ns.

The configuration choice is performed by a quantum random number generator (QRNG) placed at the interferometer output. The timing ensures that any information about the configuration choice should travel at  $4$  times the speed of light to influence the photon behavior at the entrance [2].

We have observed interference with a visibility  $V = 94\%$  as well as an anticorrelation parameter  $\alpha = 12\%$ , both in the delayed-choice mode, in full agreement with quantum mechanics predictions.

### 3 THEORETICAL ANALYSIS

As stated above, the goal of the experiment is to disprove theories where the light-pulse behaves either like a wave or a particle, depending on the experimental setup. We present here a quantitative model of this behavior, and confront it to the experimental results reported above. Note that such experiment can be perfectly explained by other theories exhibiting a wave-particle duality, like the de Broglie-Bohm pilot-wave theory [5, 6]. Wheeler's delayed-choice experiment tests against particle-OR-wave theories, as opposed to particle-AND-wave theories, like quantum mechanics or the pilot-wave theory.

In a particle-or-wave theory, the behavior of the light-pulse is quantified by the probability  $p_w$  to behave like a wave, and the complementary probability  $p_p = 1 - p_w$  to behave like a particle. The dependence of this behavior on the interferometer configuration is characterized by the probability  $p_{w|o}$  (resp.  $p_{w|c}$ ) of a wave-like behavior when the interferometer is open (resp. closed).

When the interferometer configuration choice is random and relativistically separated from the entrance of the photon in the interferometer, this choice cannot influence the photon behavior, imposing  $p_{w|o} = p_{w|c}$ .

The interference visibility  $V$  quantifies the wave aspect of the light-pulse when the interferometer is closed. It depends of the optical pathlength difference between the two arms, which can only influence something (*e.g.* a wave) which simultaneously travels along bthe two arms. A single classical particle, on the contrary, has to choose its path and will not be sensitive to this path difference, leading to  $V = 0$  when the light-pulse behaves like a particle. Therefore, one has  $V \leq p_{w|c}$ .

The anticorrelation parameter  $\alpha$  obeys  $\alpha \geq 1$  for any theory where the light is described by a wave, but decreases to zero for classical single particles. It is therefore a measure of the particle-like behavior [4], with the constraint  $\alpha \geq p_{w|o}$ .

These inequalities show that a wave-or-particle theory can only explain experimental results in the delayed-choice regime if  $V \leq \alpha$ . On the other hand, if  $V > \alpha$ , as in our experiment where  $V = 94\%$  and  $\alpha = 12\%$ , this can only be explained by either a wave-and-particle theory, like quantum mechanics, or by an information leakage from the QRNG to the light-pulse.

To quantify the amount of information leakage needed to explain the observed values of the parameters  $V$  and  $\alpha$ , we need to compute a lower bound for the probability of the light-pulse to correctly “guess” the interferometer configuration. This probability is constrained by the conditional probability  $p_{c|w}$  (resp.  $p_{o|p}$ ) for the interferometer to be closed (resp. open) knowing the light behaves like a wave (resp. like a particle). Applying Bayes theorem, one has

$$p_{c|w} = \frac{p_{w|c}}{p_{w|o} + p_{w|c}} \geq \frac{V}{V + \alpha} > 88\%; \quad p_{o|p} = \frac{1 - p_{w|o}}{2 - p_{w|o} - p_{w|c}} \geq \frac{1 - \alpha}{2 - V - \alpha} > 93\%.$$

Assuming a symmetrical probability for the light to correctly “guess” the QRNG output (*i.e.*  $p_{c|w} = p_{o|p}$ ), this probability is therefore greater than 93%, which is hardly compatible with the estimated 52% predictability of the QRNG [2].

In conclusion, the experimental results can only be explained if the light-pulse is described by either (1) a wave-and-particle theory, like quantum mechanics; (2) a wave-or-particle theory where information on the setup can travel at 4 times the speed of light; (3) a wave-or-particle theory and our QRNG exhibits undetected correlationstaht could be detected with probability a higher than 93%. Needless to say, the most reasonable option seems to be the first one!

## References

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