Timing-induced quantum collapse of wave-particle duality in a two-path interferometer

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We propose an experiment of two-path interference in which the optical path difference between the two interferometer arms is much larger than the spatial spread of single-photon pulses, thereby enabling the “which-path” information of an individual photon to be identified, without disturbing its passage at all, by measuring its time of flight. This apparently simple experiment poses a few conceptual puzzles, including the suggestion of inevitability of the von Neumann-Wigner interpretation of quantum mechanics.

Wave-particle duality is a central concept of quantum mechanics, which holds that every quantum object possesses properties of both waves and particles, appearing sometimes like a wave, sometimes like a particle, in different observational settings. Whether a quantum object is in the state of being a wave or a particle cannot be presupposed until it is measured. This striking fact is further intensified in Wheeler’s delayed-choice experiment [1], where the choice of whether or not to measure which path the photon travels through can be made only after the photon has entered the two-path interferometer.

To understand Wheeler’s delayed-choice experiment, consider a Mach-Zehnder interferometer as sketched in Fig. 1. A single-photon pulse is fired from the single-photon source and split by the first beam splitter BS\textsubscript{in} into the two paths. In the “closed” configuration, the two paths are recombined by a second beam splitter BS\textsubscript{out} before the photon strikes either of the two detectors. The detection probabilities at D\textsubscript{1} and D\textsubscript{2} exhibit the wave nature of interference between Path\textsubscript{1} and Path\textsubscript{2} in the sense that they appear as modulated as \(\cos^2(\Phi/2)\) and \(\sin^2(\Phi/2)\), respectively, in response to an adjustable phase shift \(\Phi\), which is introduced by inserting a phase-shift plate into one of the two paths [1]. On the other hand, in the “open” configuration, where BS\textsubscript{out} is removed, the detection probabilities exhibit the particle nature of moving along a specific path, because whether a photon has traveled Path\textsubscript{1} or Path\textsubscript{2} can be inferred from whether it clicks a signal at D\textsubscript{1} or D\textsubscript{2}, respectively. There is no interference between the two paths and the detection probabilities are independent of \(\Phi\).

As the open and closed configurations are mutually exclusive (namely, the beam splitter BS\textsubscript{out} cannot be present and absent at the same time), the result of Wheeler’s delayed-choice experiment is in accord with Bohr’s principle of complementarity [2]: Wave and particle properties of a quantum object cannot be measured simultaneously and which property is manifested is determined by the type of measurement performed on it. What is truly astonishing is that the same result is obtained even if the choice between the open and closed configurations is made after the entry of the photon into the first beam splitter. In a sense, a choice made in a later moment can retroactively collapse a quantum state in the past. While it remains debatable how Wheeler’s delayed-choice experiment should be interpreted, its anticipation has been confirmed in various actual experiments [3–9].

To make the problem of collapse even more puzzling, we propose an experiment modified from the closed configuration of Wheeler’s delayed-choice experiment as sketched in Fig. 2. Here, the second beam splitter is always fixed and the optical path length \(L_2\) of Path\textsubscript{2} is arranged much larger than the optical path length \(L_1\) of Path\textsubscript{1}. Meanwhile, we prepare two high-precision clocks, C\textsubscript{e} and C\textsubscript{d}, which, by choice, may be coupled to the single-photon emitter and the detectors, respectively.

By coupling C\textsubscript{e} and C\textsubscript{d} to the emitter and detectors, one can record a photon’s departure time when it is emitted from the emitter and arrival time when it clicks a single at either D\textsubscript{1} or D\textsubscript{2}. Provided C\textsubscript{e} and C\textsubscript{d} are well synchronized, the time of flight from the emitter to the detectors can be inferred. If the difference between \(L_1\) and \(L_2\) is made much larger than the spatial spread \(\Delta x\) of a single-photon pulse and the clock precision (multiplied by the speed of light \(c\)), by timing the time of flight of each single-photon pulse, which path the photon has traveled can be unambiguously identified, regardless...
of whether $D_1$ or $D_2$ registers the signal. As a consequence, the detection probabilities at $D_1$ and $D_2$ appear independent of $\Phi$. On the other hand, if one choose to decouple $C_d$ from the detectors, as long as the choice is made before time has elapsed by $L_1/c$ since the photon’s departure time, whether the photon travels Path$_1$ or Path$_2$ remains unknown and therefore the detection probabilities at $D_1$ and $D_2$ exhibit the interference between Path$_1$ and Path$_2$ as modulated with $\Phi$. This result is akin to that of Wheeler’s delayed-choice experiment but is conceptually more striking in various aspects.

In Wheeler’s delayed-choice experiment, the choice between keeping or removing the second beam splitter does make a change upon the routes a photon may travel. In the new experiment, by contrast, coupling or decoupling $C_d$ only affects the detectors (in whatever sense) but apparently makes no disturbance upon the routes at all. It is curious why the photon’s behavior is nevertheless altered.

Conversely, if we keep $C_d$ engaged but choose to or not to decouple $C_e$ from the emitter before a photon is fired, recording of the departure time can be enabled or disabled, and therefore the time of flight may or may not be inferable. Consequently, we can turn on or off the two-path interference at will simply by coupling or decoupling $C_e$. Why does mounting or dismounting a clock on the emitter make a change for the behavior of photons it emits?

One might argue that, even though the clocks do not affect the travel routes, a photon can still manage to “sense” the presence of $C_d$ or $C_e$ by analogy to the Aharonov-Bohm effect, where a charged particle is affected by an electromagnetic field that is applied outside the particle’s travel routes. However, the corresponding electromagnetic potential (or more rigorously, the hololomy of it) is nonzero along the passage, which is responsible for the Aharonov-Bohm effect. In our proposed experiment, by contrast, there is no obvious analog of the electromagnetic potential. Furthermore, in the absence of $C_e$, engaging or disengaging $C_d$ makes no difference any more; nor does engaging or disengaging $C_e$ in the absence of $C_d$. In other words, what a photon seems to sense is not the presence of $C_d$ or $C_e$ per se but instead the “togetherness” of them. This is a striking feature not found elsewhere.

If the issues raised above still do not seem baffling enough, then consider a scale-up setting in which $L_2$ is prolonged to the extent that $(L_2-L_1)/c$ reaches several seconds. In this case, without the help of any clocks, the experimenter can measure a photon’s time of flight simply by counting in his mind the time elapsed from the moment when he presses the button of the emitter to the moment when one of the detectors beeps a signal. If he keeps attentive, the accuracy of his mental counting of time can be fairly within a second or two. Consequently, which way a photon has traveled can be identified and the detection probabilities are independent of $\Phi$. On the other hand, if he keeps absent-minded, the which-way information of a photon remains undetermined and the detection probabilities exhibit the two-path interference.

It is astonishing that, apparently, the state of a photon can be collapsed solely by the experimenter’s mindfulness and nothing else at all. Moreover, if two or more inspectors observe the experiment at the same time, a photon will behave as a particle if and only if any of them is counting time in mind. In a sense, this experiment can be used as a kind of mind reader! If this result indeed happens, it will deliver an unequivocal verdict in favor of the von Neumann-Wigner interpretation of quantum mechanics, which posits that it is essentially consciousness that causes collapse.

The scale-up experiment seems far beyond the reach of current technology. To have $(L_2-L_1)/c$ exceed a few seconds, $L_2 - L_1$ has to be $\geq 10^9$ m long. It is extremely difficult to keep a light wave coherent between two paths with such a huge optical path difference even for a stationary source (of which the coherence length is about ~1 km for commercial lasers of wave-
length ~500 nm [13], let alone for a single-photon source. Furthermore, there might be some fundamental reasons that prohibit the proposed experiment from being arbitrarily scaled up. For example, according to objective collapse theories, e.g. [14,15,17,19, and 20], a quantum state in superposition is collapsed (localized) spontaneously when a certain objective physical threshold is reached. In our case, it is quite likely that the underlying detection mechanism of a single-photon detector sets a threshold for the time delay between a photon’s two wavefunction components supposed to arrive at the detector at different times, and therefore the interference between the two paths is erased once $|L_1 - L_2|$ reaches a certain scale (probably far below ~1 km), irrespective of any timing devices or an inspector’s mind. At this moment, it is uncertain whether the difficulty of scaling up the experiment is purely technological or intrinsically unavoidable. If the difficulty proves fundamentally inevitable, it will remain needless to appeal to any anthropocentric interpretation of quantum mechanics.

It is worthy of mentioning again that, in order to determine a photon’s which-way information by timing its travel, $L_2 - L_1$ has to be much larger than the spatial spread $\Delta x$ of a single-photon pulse as well as the clock precision. The condition $\Delta x \ll |L_1 - L_2|$ suggests that the trace of a single-photon pulse following Path 1 and that following Path 2 do not overlap each other again once they are separated by BS$_i$. This arouses doubt that the single-photon interference could be obtained at all. This doubt, however, is due to the confusion between the spatial spread $\Delta x$ and the coherence length $\ell_c$ of a single-photon pulse. The required condition for the interference to appear is $\ell_c > L_1, L_2$, not necessarily $\Delta x > |L_1 - L_2|$. It is not difficult to produce single-photon interference while keeping $\Delta x \ll |L_1 - L_2|$, and this has been considered in the literature. For example, in the experiment of the Bell inequality for position and time proposed in [21] and carried out in [22,23], the observable effects that are used to demonstrate inconsistency with any local hidden-variable theory rely on the interference between $L_1$ and $L_2$ under the condition $\Delta x \ll |L_1 - L_2|$.

Meanwhile, it should be emphasized that, as well as Wheeler’s delayed-choice experiment, our proposed experiment concerns the single-particle (single-photon) effect. It should not be confused with the Hanbury Brown and Twiss (HBT) effect [24–26], which essentially involves two-particle amplitudes [27], despite the fact that the HBT experiment also times the detection signals and may require the two paths to have significantly different lengths. To carry out the proposed experiment, the ensemble of emitted single-photon pulses have to be temporally well separated to neglect any contamination from many-particle effects.

Finally, we remark on the fact that the technology required to conduct the proposed experiment is well within reach, except for the scale-up setting. For example, in the experimental realization of Wheeler’s delayed-choice experiment made in [9], the two paths are ~50 m long, and the spatial spread of a single-photon pulse and the resolution of timing have to be smaller than ~5 m in order to ascertain that the delayed-choice is made after a photon has entered the interferometer. Adopting the same technology and setting $L_1$ and $L_2$ to be about ~50 m and ~100 m long, respectively, one should be able to realize the proposed experiment. If any experimental result does not happen as anticipated for some unknown reason, it will entail a drastic revision to our understanding of wave-particle duality.

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