Einstein's Bubble: Experimental search for "Empty Waves"

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Abstract: We investigate nature of the wavefunction collapse in a *welcher weg* experiment by observing physical effects of the so-called "Empty Waves," specifically their ability to interfere with real photons to generate spatial or temporal interference.

The nature of the quantum wavefucntion, and its collapse, upon the measurement of its associated particle, has been the source of intense debate since the foundation of the quantum mechanics. It was dramatically demonstrated by Einstein's famous nonlocal "popping" of the wavefunction "bubble" in the 5th Solvay conference in 1927 [1]. To date, all experiments have failed to show that the collapse does not occur, however, in quantum optics, the mere possibility that the wavefunction does not entirely disappear *after* destructive measurement of its associated photon, is of significant interest to the field of quantum computing and communication and needs to be studied.

We investigate the nature of the wavefunction (WF) collapse in a *welcher weg* experiment by observing the physical effects of the so-called "empty waves" (EWs). More specifically, we scrutinize their ability to interfere with pulses carrying real photons in order to generate first order interference effects. We superpose the expected EW of an already-detected photon with the temporally-separated WF of a second photon. Fig. 1 depicts the essential schematic elements of this experimental set up.

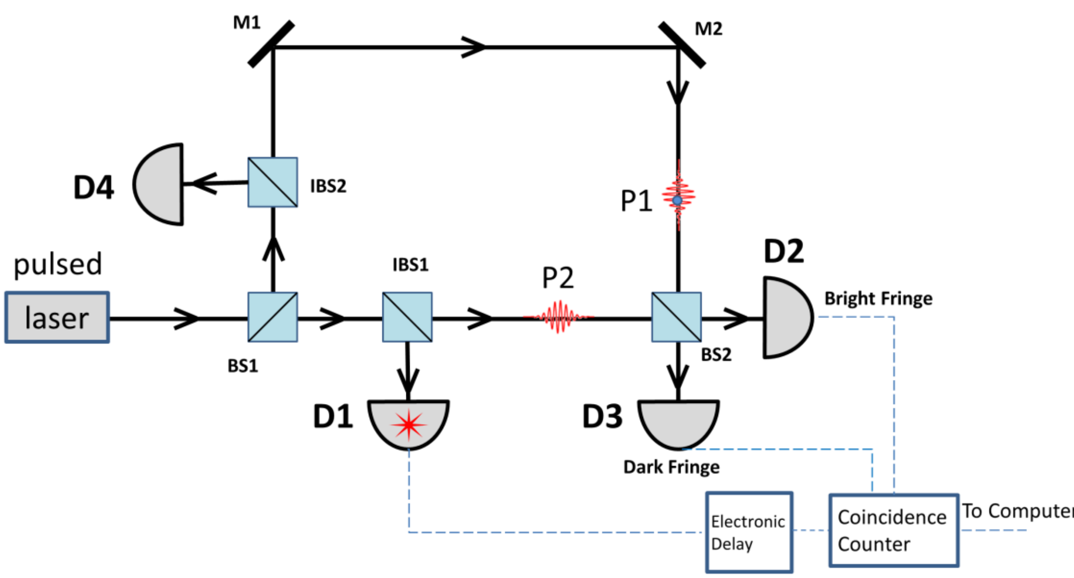

Fig. 1. Experimental setup. An optically chopped CW laser at 633 nm, is attenuated and pairs of pulses separated by the optical path difference of the setup are sent into an asymmetric MZI, with BS1 as input and BS2 as the output beamsplitters. Additional "interrogator" beamsplitters IBS1 and IBS2 are placed immediately after BS1 on short and long arms of the MZI respectively. Single photon detectors D1-4 are high efficiency SPADS or cryogenic superconducting nanowire detectors. Here only a relevant post-selected event is depicted at the moment that D1 has detected the photon in the lower arm, and therefore according to the Copenhagen interpretation, pulse P2 should collapse and only the vacuum state remains. Alternatively, P2 can be thought of as an "empty wave," devoid of the photon particle, but still moving at the speed of light in the medium, and carrying the phase "information". The experiment is designed such that all photons arrive at D2, and none at D3 because of the high visibility of the first order interference. The output of D1 is electronically delayed to compensate for the optical path difference between D1 and D2 (D3) and then sent into a coincidence counter. A full 2-way, 3-way and 4-way coincidence analysis is performed on the output of all four detectors (here we only show a 3-way coincidence counting scheme).

We send pairs of very weak, highly coherent pulses of 633 nm CW laser light of duration of 5-10 ns, into an asymmetric MZI. Due to its sharp spectral linewidth, the coherence length of the laser is much larger than the experimental setup. To ensure overlap of consecutive pulses P1 and P2 at the final beamsplitter BS2, the temporal separation of the pair of pulses is set to ΔT = OPD/c, c being speed of light in the medium, and OPD the optical path difference (OPD) of the long and short arms of the MZI. The repetition rate of the pair of pulses is limited only by the maximum count rate of the detectors.

Both long and short arms of the MZI have an additional interrogator beamsplitter (IBS) early in each path (IBS1 and IBS2) so that interrogator photon detectors (IPDs) D1 and D4 can detect the presence of a photon in each arm if any. Due to the Poisson characteristics of coherent light, occasionally a photon and an EW arrive at the final BS2 simultaneously, temporally separated by ΔT = OPD/c. The optical paths are chosen such that all photons arrive at D2 due to constructive interference, and no photons arrive at the D3 due to destructive interference. D2 and D3 are equidistant from BS2. It is important to note that interference only occurs when the two pulses arrive at the same time, and these events are post-selected by matching the sync clock pulses with the signal events. Coincidence rate of IPDs and detectors at BS2 outputs are measured. Observation of any change in coincidence rates that corresponds to interference phenomena would suggest the presence of a physically real empty wave. **If the empty wave does *not* exist, then both D2 and D3 have equal likelihood of detecting the photon. However, if the empty wave *does* exist, only D2 will detect and D3 will never detect (assuming ideal classical interference conditions).**

Since it is impossible to create first-order interference in an asymmetric MZI with Fock state single photon sources due to their extremely small coherence lengths, we chose to use extremely low flux CW laser pulses in which only 1 out of 100 pulses contain a single photon on average. In such a case, while not number state, due to Poissonian nature of the coherent light, 99.5% of detection events are single photon events, and only 0.5% are two or multi-photon events, allowing us to obtain the which-way information of the detected photons at better than 99% accuracy. In this manner we ensure a stable phase relation between up to 10,000 pulse pairs, and achieve high visibility interference, while ensuring with high confidence only single photon is present in each arm of MZI.

Tables 1, and 2 tabulate the statistically relevant joint Poisson probabilities, as well as all 2-way coincidence rates. The highlighted cells in each table are the post-selected population of detections that can provide an answer to weather P2 (Empty Wave) can cause interference. Ideally, if all of the P1 photons end up at D2, and none at D3, it would provide the first physical evidence of the reality of Empty Waves. **However, due to the inevitable experimental errors, if the rate of detections at D3 is measurably less than 50% of the post-selected events corresponding to interference, it would herald the discovery of the physical reality of the Empty Waves.**

Tables 1. Joint Poisson Probabilities

	𝒫 (0)	**𝒫 (1)**	**𝒫 (2)**	**𝒫 (3)**
𝒫 (0)	𝒫(0,0)	𝒫(1,0)	𝒫(2,0)	𝒫(3,0)
𝒫 (1)	𝒫(0,1)	𝒫(1,1)	𝒫(2,1)	𝒫(3,1)
𝒫 (2)	𝒫(0,2)	𝒫(1,2)	𝒫(2,2)	𝒫(3,2)
𝒫 (3)	𝒫(0,3)	𝒫(1,3)	𝒫(2,3)	𝒫(3,3)

Table 2. All 2-way coincidence rates

	D1	**D2**	**D3**	**D4**
D1	$N(1,1)$	$N(1,2)$	$N(1,3)$	$N(1,4)$
D2	$N(2,1)$	$N(2,2)$	$N(2,3)$	$N(2,4)$
D3	$N(3,1)$	$N(3,2)$	$N(3,3)$	$N(3,4)$
D4	$N(4,1)$	$N(4,2)$	$N(4,3)$	$N(4,4)$

Finally, we note that the detectors are state of the art cryogenic superconducting nanowire sensors, with an individual system detection efficiency of over 95% and unprecedented combined detections efficiency of over 80%. A fiber optics version of the experiment is currently under construction, and time permitting, the most up to date results will be presented at the Q.C. 2.0 conference in June of 2023.

[1] A. Einstein, in *Electrons et Photons - Rapports et Discussions du Cinqui'ème Conseil dePhysique tenu, Bruxelles du 24 au 29 Octobre 1927 sous les Auspices de l'Institut International de Physique Solvay*, Gauthier-Villars, Paris (1928).