

## Phase shifting of an interferometer using nonlocal quantum-state correlations

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We describe an experiment where the phase and amplitude of the interference pattern of light going through an interferometer was varied by doing operations on quantum-correlated light that did not go through the interferometer. This was accomplished by sending a pair of polarization-entangled photons in separate directions, one to an interferometer and the other one to a phase shifter, in principle in a remote location. The interferometer was set up to put the state of the pair in a superposition of maximally entangled states. The phase shifter inserted a phase between the product-state components that made up each entangled state. Polarizers located before the detectors projected the quantum state of the light. As a result, the phase and amplitude of the interference pattern were varied by changing the settings of the phase shifter and polarizer in the path of the photon in the remote location.

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Interferometry with light is a basic measurement technique in science and technology. From a classical-wave standpoint, interference is well-understood, and metrology based on interference of light is a mature field. Yet, progress in the field of quantum information has led to a fundamental reexamination of interference of light from a quantum mechanical perspective. As a result, new techniques have emerged that use light in quantum interference, such as quantum teleportation [1,2] and quantum cryptography [3]. In other cases, quantum-correlated photons have enabled a new way of doing measurements [4].

Consider, for example, an amplitude-splitting interferometer, such as a Mach-Zehnder interferometer. Changes in the phase of the interference pattern are produced by changes in length of the arms of the interferometer or by changes in the settings of optical components in the interferometer. The interference disappears when the path length difference exceeds the coherence length of the light. In quantum mechanics interference manifests in the probability amplitudes of the photon taking the indistinguishable paths of the interferometer [5]. Interference disappears when the paths become distinguishable. Thus one can view the coherence length as the length of the wave packet of the photon. As the path-length difference becomes greater than the coherence length the paths become distinguishable because the photon will arrive at distinguishably different times depending on the path that it takes [6].

Quantum interference may encompass more than just light: other particles or even the measuring apparatus can also be a factor in producing the interference pattern. Interference with correlated photons has led the way in reexamining quantum interference using light [7]. The generality of the definition makes us think more broadly about interference, enabling us to devise schemes that do not arise naturally from a classical perspective. Thus we may think about making the quantum interference disappear by ways other than increasing the path-length difference. It suffices to make the paths distinguishable by any means. In addition, this distinguishable action can be made by delayed choice after the light passed through the interferometer [8,9], or even after the light has been detected [10].

The experimental arrangement of Franson [11], demon-

strated experimentally numerous times [12], uses two interferometers placed in the paths of correlated photons. The interferometers can be very far away from each other [13]. The difference in the arm lengths of the interferometers can be larger than the coherence length of the down converted light but less than the coherence length of the pump light. The interference appears in the coincidence counts from the detectors placed after the two interferometers. The probability amplitudes depend on the phases of the indistinguishable ways of producing coincidences.

So far experiments with a single interferometer have exploited the idea that the amplitude of the interference pattern can be reduced to zero by changes or projections in the state of the light. It has been shown recently that by using entangled states of light the amplitude can be changed nonlocally by actions on the partner photon that does not go through the interferometer [14–16]. This essentially amounts to a quantum mechanical projection of the entangled state of the light. In addition, the actions that make the paths distinguishable are nondestructive [9,17]. That is, the distinguishability can be reverted (i.e., erased) or recovered by further projections of the state of the light.

Classically the phase of the interference pattern is introduced locally in the interferometer, by either a dynamical phase (e.g., changing the length of one of the arms of the interferometer) or a geometric phase (e.g., Pancharatnam phase). Here we demonstrate the possibility of using quantum mechanics to change the phase of the interference “remotely,” i.e., via manipulations on quantum-correlated photons that are in a remote location. We use an interferometer for one of the photons of a correlated pair and a phase shifter for the other “remote” photon. It also requires that the photon pairs be entangled by polarization. We change the phase of the interference pattern by manipulating the quantum state of the light via actions on the remote entangled partner. That is, the portion of the light enabling the phase shift does *not* go through the interferometer. We can also view this as changing the phase of the interference pattern nonlocally.

Our method is based on two types of quantum mechanical manipulations. One uses the quantum correlations of polarization entangled photon pairs as a function of the phase between the product states that make up the entangled state.

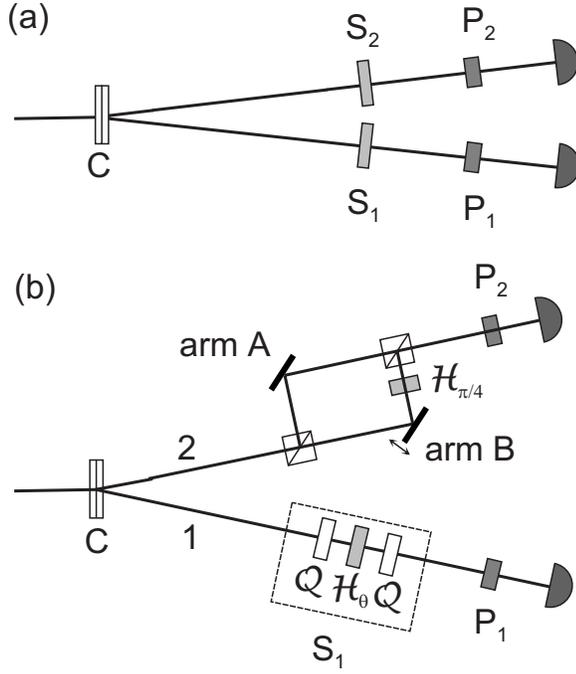


FIG. 1. Setup to study phase correlations between polarization-entangled photons. Crystal C produces photons via parametric down conversion. Polarizers  $P_1$  and  $P_2$  project the state of the photons before being detected. In (a) photons go through phase shifters  $S_1$  and  $S_2$ . In (b) one photon goes through a geometric-phase shifter  $S_1$ , and the other one goes through a Mach-Zehnder interferometer.

The other manipulation, developed by us recently [16], uses the interference of two polarization-entangled states via the arms of an interferometer.

A classic setup to investigate nonlocal quantum correlations of two light quanta involves a source of polarization-entangled photons and polarizers placed in the path of each photon. The record of the coincidences in the detection of the two photons as a function of the orientation of the polarizers yields correlations that have been used to measure violations of Bell's inequalities to varying degrees of precision (see, for example, Ref. [18]). Another simple correlation test involves varying the state of the entangled photons while keeping the polarizers at fixed orientations [18]. This is done by introducing a phase between the product states of the entangled state shared by the two photons.

Here we consider this correlation further. A schematic of this setup is shown in Fig. 1(a). Pairs of photons produced by parametric down-conversion are prepared in the state  $|\Phi^+\rangle = 2^{-1/2}(|H\rangle_1|H\rangle_2 + |V\rangle_1|V\rangle_2)$ .  $|H\rangle$  and  $|V\rangle$  represent the states of linear polarization of the light: horizontal and vertical, respectively. Labels 1 and 2 denote the two photons. We place phase shifters  $S_1$  and  $S_2$  in the path of both photons that introduce respective phase shifts  $\phi_1$  between the polarization states  $|H\rangle_1$  and  $|V\rangle_1$ , and  $\phi_2$  between  $|H\rangle_2$  and  $|V\rangle_2$ . Thus after the phase shifters the state of the light is  $|\Phi^+\rangle = 2^{-1/2}[|H\rangle_1|H\rangle_2 e^{i(\phi_1+\phi_2)} + |V\rangle_1|V\rangle_2]$ . Polarizers  $P_1$  and  $P_2$  placed after the phase shifters and with transmission axes oriented at angles  $\theta_1$  and  $\theta_2$  relative to the horizontal, respectively, project the state of the light. When  $\phi_1 = \phi_2 = 0$  we obtain the well-known result for the probability of detecting

the pair:  $P = (1/2)\cos^2(\theta_1 - \theta_2)$  [19]. However, we obtain a more general result when we allow  $\phi_1$  and  $\phi_2$  to vary. If we consider the particular case  $\theta_1 = \theta_2 = \pi/4$ , then the detection probability has an interesting form:

$$P = [1 + \cos(\phi_1 + \phi_2)]/4. \quad (1)$$

Because the phase shifters alter the quantum state of the light, they introduce this correlation involving the two phases.

We also use state manipulation studied recently by our group, where an interferometer is used to interfere different maximally entangled states [16]. Consider the schematic of our apparatus, shown in Fig. 1(b), and for the moment ignore the components within the dashed-line box  $S_1$  in the figure. Polarization-entangled photons are produced by parametric down-conversion, with photons 2 going through a Mach-Zehnder interferometer. We prepare the entangled state of the photons to be  $|\Phi^+\rangle = 2^{-1/2}(|H\rangle_1|H\rangle_2 + |V\rangle_1|V\rangle_2)$  when arm B of the interferometer is blocked. Arm B of the interferometer has a half-wave plate [ $\mathcal{H}_{\pi/4}$  in Fig. 1(b)] with its fast axis forming an angle of  $\pi/4$  with the horizontal. The wave plate switches the polarization state of photon 2 to its orthogonal state. This way the state of the pair is  $|\Psi^+\rangle = 2^{-1/2}(|H\rangle_1|V\rangle_2 + |V\rangle_1|H\rangle_2)$  when arm A of the interferometer is blocked. As a consequence, when both arms are unblocked the state of the light past the through port of the interferometer is  $|\psi\rangle = 2^{-1/2}(|\Phi^+\rangle + |\Psi^+\rangle e^{i\delta})$ . The dynamic phase  $\delta$  is due to the path length difference in the arms of the interferometer. The state of the light is further projected by a polarizer  $P_1$  placed in the path of photon 1. The probability of detecting a pair is  $P = (1 + \sin 2\theta_1 \cos \delta)/4$ . That is, the visibility of the interference pattern is determined by the orientation of the polarizer in the path of photon 1, which does not go through the interferometer [16].

In this work we added a Pancharatnam-Berry phase shifter  $S_1$  [within the dashed-line box of Fig. 1(b)] in the path of photon 1 and before the polarizer  $P_1$ . The phase shifter introduced a phase  $\phi$  between the horizontal and vertical components of the polarization of photon 1. When  $\phi = 0$  the states that interfere are  $|\Phi^+\rangle$  and  $|\Psi^+\rangle$ , as mentioned earlier. As  $\phi$  was varied the interfering states transformed, evolving, respectively, into  $|\Phi^-\rangle = 2^{-1/2}(|H\rangle_1|H\rangle_2 - |V\rangle_1|V\rangle_2)$  and  $|\Psi^-\rangle = 2^{-1/2}(|H\rangle_1|V\rangle_2 - |V\rangle_1|H\rangle_2)$  when  $\phi = \pi$ . It can be shown that when we place a polarizer  $P_2$  after the interferometer with its transmission axis aligned with the vertical (i.e.,  $\theta_2 = \pi/2$ ), the probability of detecting the pair becomes

$$P = [1 + \sin 2\theta_1 \cos(\delta + \phi)]/8. \quad (2)$$

What is striking about the above relation is that the phase  $\phi$  appears in the phase of the interference pattern as an *additive* contribution to the dynamical phase  $\delta$ . The expression for the probability at an arbitrary angle  $\theta_2$  is not as simple as Eq. (2). However, for the sake of simplicity we will limit ourselves to the case where  $\theta_2 = \pi/2$ . One could arrive at the same result by applying the state projection of the pair by  $P_1$  before photon 2 enters the interferometer. That is, the order in which we do this does not matter. The key element remains the

introduction of the phase  $\phi$  between the product states of the initial entangled state.

In our experiments, 915.6-nm polarization-entangled photons were produced by parametric down-conversion of the 457.8-nm light of an argon laser (100 mW) via two stacked 1-mm-thick type-I beta-barium-borate crystals [20]. The preparation of the entangled state was tuned by tilting a birefringent plate (not shown) that was placed in the path of the pump beam [16,20]. We verified the entanglement by performing a Clauser-Horne-Shimony-Holt test of Bell's inequalities [21] via changes in the orientations of the polarizers  $\theta_1$  and  $\theta_2$ , and obtained a violation of the Bell inequality given by  $S=2.39\pm 0.09$  (local behavior is predicted to yield  $S<2$ ). The extra path length added by the half-wave plate  $\mathcal{H}_{\pi/4}$  in arm *B* of the interferometer was compensated by a pair of crystals placed in arm *A* (not shown).

The phase shifter  $S_1$  was a classic Pancharatnam-Berry phase shifter, consisting of two quarter-wave plates [ $\mathcal{Q}$  in Fig. 1(b)] with their fast axes forming an angle of  $-\pi/4$  with the horizontal, and with a rotating half-wave plate ( $\mathcal{H}_\theta$ ) in between them [22]. When the half-wave plate was turned by an angle  $\beta+\pi/4$  the horizontal component acquired a geometric phase  $+2\beta$  and the vertical component acquired a geometric phase  $-2\beta$ . Thus the phase difference between the two polarization states  $H_1$  and  $V_1$  was  $\phi=\phi_1=4\beta$ .

The detection apparatus was the same used previously [16]. Briefly, the down-converted light was detected by bare avalanche photodiodes (APD) in detector arrangements housed in an ambient-light-tight box with windows covered by wide bandpass filters. Inside the housing each APD was preceded by an iris with a diameter of 1 to 2 mm, followed by a lens with a focal length of 10 cm, and a narrow bandpass filter centered at the down-converted wavelength. The narrow-bandpass filters in the path of photons 1 and 2 had bandwidths of 1 and 10 nm, respectively. The 1-nm filter was needed to better specify the retardance of the various waveplates in the setup and to specify the coherence length of the light. It was placed in the path of photon 1 to further underscore the correlated-light nature of the experiment [14]. The low efficiency of the optical system in combination with the low efficiency of the detectors at the down-converted wavelength contributed to a low count rate of coincidences.

We verified the prediction of Eq. (2) in two ways: by recording the interference pattern as a function of  $\beta$  and by varying the dynamic phase  $\delta$  for different values of  $\beta$ . Figure 2 shows a graph of the coincidences as a function of angle of rotation of the half-wave plate  $\beta$ . The phase  $\delta$  was kept fixed while the angle  $\beta$  was scanned by means of a stepper-motor-driven rotation stage. A fit to the data yielded  $\phi/\beta=3.7\pm 0.3$ , consistent with the expected value of 4. This data was taken for  $\theta_1=\pi/4$  and  $\theta_2=\pi/2$ . Not shown are an additional set of scans that we took that confirmed a different aspect of Eq. (2). They consisted of observing the interference pattern as a function of  $\beta$  for different values of  $\theta_1$ . The observed visibilities reduced to zero as  $\theta_1$  was increased from  $\pi/4$  to  $\pi/2$ . Fits to the data gave a value of  $\phi/\beta$  consistent with the expected value of 4 (e.g.,  $\phi/\beta=4.1\pm 0.3$  for a typical scan).

Figure 3 shows a graph of the coincidences as a function of  $\delta$  for different values of  $\beta$ . The dynamic phase  $\delta$  was

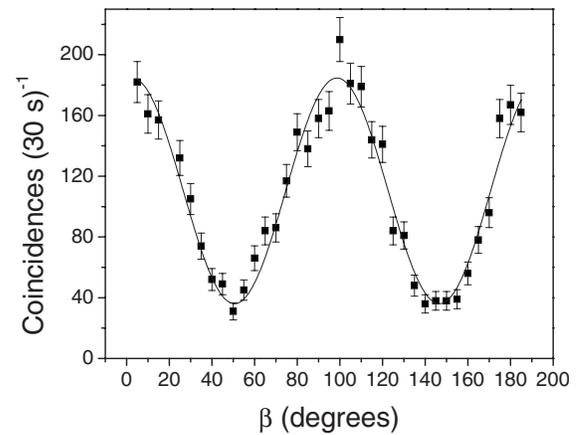


FIG. 2. Graph of the measured coincidences as a function of the rotation angle  $\beta$  of the geometric-phase shifter that was in the path of photon 1. The solid line is a fit to the data.

changed by pushing one of the mirrors of the interferometer using a piezoelectric ceramic placed as a spacer on the translation stage where the mirror was mounted. The difference in length of the two arms of the interferometer was changed by increasing stepwise the voltage on the piezoelectric  $V_p$ . The orientation of the half-wave plate  $\mathcal{H}_\theta$  was changed when  $V_p$  was 42.0 and 74.25 V. At those points of the scan the phase  $\beta$  was increased by  $\Delta\beta_1=\pi/8$  and  $\Delta\beta_2=\pi/4$ , respectively. As can be seen in Fig. 3, the phase of the scan shifts abruptly at the two values of  $V_p$  where  $\beta$  was changed. Fits to the data gave phase jumps  $\Delta\phi_1=(1.1\pm 0.3)\pi/2$  and  $\Delta\phi_2=(0.93\pm 0.10)\pi$ , which agree with the expected jumps  $\Delta\phi=4\Delta\beta$ .

In summary, we report a measurement scheme involving a conventional light interferometer where by measuring the coincidence detections of photons going through an interferometer and entangled partners going through a phase shifter, we

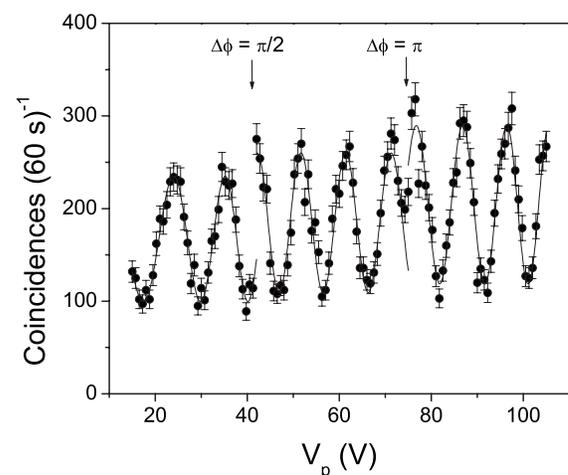


FIG. 3. Graph of the measured coincidences as a function of the phase imparted to photon 2 via the voltage on the piezoelectric that changed the length of arm *B* of the interferometer. Two abrupt changes in the phase were caused by changes in the remote phase  $\phi$  via the angle  $\beta$  of the phase shifter in the path of photon 1. The solid curves are fits to the data.

were able to record interference patterns whose amplitude and phase were changed by actions on the photons that did not go through the interferometer. We note that for simplicity we used only one phase shifter. We could have put a phase shifter  $S_2$  in the path of photon 2 before the light went through the interferometer. This way the phase  $\phi$  in Eq. (2) would have a contribution  $\phi_2$ , as shown in Eq. (1). Moreover, there could be more phase shifters in the paths of the two photons, in which case the argument of the cosine term of Eqs. (1) and (2) would be the sum of all the phases. These types of correlations obtained by changing the phases may offer new possibilities of performing tests of Bell's inequalities, where we change the quantum state of the light but keep the state-projecting polarizers fixed.

By adding a phase control this experiment further reinforces a rethinking of the paradigm of interference as a local measurement. That is, the phase of the interference pattern can contain components due to measurements in a remote location. It is interesting that this has potential applications in interferometry, by sensing in one location and recording in

another location. In the language of quantum communication [23], Alice performs the physical actions to do the measurement on a "sensor" photon and then tells Bob, who is in a remote location, when to record. Alice's measurement can then be read out by Bob via the oscillations in the coincidences (i.e., fringes of the quantum interference pattern). Since the local and remote phases are additive, this technique could be used for new types of measurements where the measured quantities (local and remote) are complementary. In that case the apparatus could record the combined change in the two quantities. In principle this type of quantum interferometry could be implemented in other physical quantum systems, and therefore expand the applications of the technique.

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