Interference of quantum channels in single photon interferometer

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We experimentally demonstrate the interference of dephasing quantum channel using single photon Mach-Zender interferometer. We extract the information inaccessible to the technology of quantum tomography. Further, We introduce the application of our results in quantum key distribution.

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Macrosopic quantum systems can never be isolated from their environments. It leads to decoherence which destroys superpositions. And when a qubit transmits through a quantum channel, the interaction between qubit and quantum channel is inevitable. The decoherence in quantum channel affects the distance and quantity of quantum information transmitting. So it is important to know what happen when quantum information transmit through noisy quantum channel. The technology of quantum process tomography[1, 2] can be used to characterize the quantum channels.

But J. Aberg[3] find that we can not specify the action of the simultaneous operation of both maps although we known the individual quantum channels. It is said that when a superposition state pass through two quantum channels, we can not know the information of output state exactly by using the technology of quantum process tomography. Single particle interference can help us extract information inaccessible to conventional process tomography. D. K. L. Oi have given a measure of coherent fidelity, the maximum interference visibility, and the closest unitary operator to a given physical process under this measure[4].

Here, We give an interference visibility of two quantum processes which have same environment degree and carry out an experiment to demonstrate it. The environment qubit is the time qubit from birefrigence of quartz crystal in the experiment, i.e. quantum channels we used is the dephasing channel. We find that there are plentiful of information of interference which is the information inaccessible to conventional process tomography[1, 2].

When a single qubit state transmits through two quantum channels (Fig. 1), how can we known the output state? The technology of quantum tomography can obtain the densities of output states in each paths. But the whole density of the output state can not be fixed, i.e. there is other information which have not been extracted. D. K. L. Oi[4] shows that single particle Mach-Zender interference can help us. Different visibilities show quantum information not presented in the two individual quantum channel. When the different environment degree (E and F) appended to the operations of the upper and lower arms, D. K. L. Oi presents the interference patterns as

\[ Tr[u_0^+ v_0 \rho], \] (1)

where \( \rho \) is the input state, \( u_0 \) and \( v_0 \) are the first Kraus operators for the quantum processes \( U \) and \( V \) in upper and lower arms. If the input state is the maximally mixed state, the interference pattern depends on \( \frac{1}{\sqrt{2}} Tr[u_0^+ v_0] \).

In Eq. 1, The interference patterns only depend on the first Kraus operators \( u_0 \) and \( v_0 \). But it find that when the environment degree is same to the operations of the both arms (Fig. 2), the interference pattern will depend on the four Kraus operators \( u_i \) and \( v_i \). The beamsplitters in Fig. 2 and the phase shifter are modeled by the unitary operators \( U_b \) and \( U_p \), respectively,

\[ U_b = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix}, \quad U_p = \begin{pmatrix} 0 & e^{i\phi} \\ 1 & 0 \end{pmatrix}. \] (2)

The original state \( \rho_{in} = |0\rangle \langle 0| \otimes \rho \) of the system on internal Hilbert space and the two-dimensional Hilbert space of path degree is evolved as

\[ \rho_{in} \mapsto U_b(|0\rangle \langle 0| U + |1\rangle \langle 1| V)U_p U_b \rho_{in} U_b^\dagger U_p^\dagger (|0\rangle \langle 0| U^\dagger + |1\rangle \langle 1| V^\dagger)U_b^\dagger \] (3)

where \( |1\rangle \) and \( |0\rangle \) represent the upper and lower path. The probability of finding the particle in the horizontal direction, i.e. in the \( |0\rangle \) state, is

\[ P_{|0\rangle}(\phi) = \frac{1}{2} (1 + Re e^{i\phi} Tr[U^\dagger V \rho \otimes |e_0\rangle \langle e_0|]). \] (4)

So \( P_{|0\rangle}(\phi) \) is decided by

\[ Tr[U^\dagger V \rho \otimes |e_0\rangle \langle e_0|] = \sum_i Tr[u_i^+ v_i \rho], \] (5)

where

\[ \{u_i\} = \{|e_i\} U |e_0\rangle\}, \quad \{v_j\} = \{|e_j\} V |e_0\rangle\}. \] (6)

are the Kraus operators of \( U \) and \( V \). Where \( \{|e_i\} \) and \( \{|e_j\} \) are the orthonormal bases of E, \( |e_0\rangle \) is the initial state of E. Specially, If the input state is the maximally mixed state, the interference pattern depends on
environment qubit (of photon passing through a BBO crystal to be the environment respectively (see Fig. 3). The Kraus operators of the indistinguishability of the two paths that the particle transmitted through. According to the interference pattern and visibility, it can be determined whether the two quantum processes are identical or different (see Fig. 3). Then beams from the two arms interact at the second beam splitter, and photon 1 is detected by single photon detector below interferometer.

\[ \sum_{i} Tr|u_{i}^{+}v_{i}\rangle \rho. \]  

The experimental setup is represented in Fig. 3. A pulse of ultraviolet (UV) light pass through a BBO crystal (1.0 mm, cut for type-I phase match). The UV pulse is frequency-doubled pulse (less than 200 fs with 82 MHz repetition and 390 nm center-wavelength) from a mode-locked Ti: sapphire laser (Tsunami by Spectra-Physics). Through the SPDC process, photon pairs are generated with 780 nm center-wavelength. By detecting one photon of the pairs (with single photon detector after a 4 nm FWHM interference filter at 780 nm), the other one (photon 1) can be prepared into any polarization state to be sent into Mach-Zender interferometer.

After a half-wave plate fixed 22.5° and a 5.0 mm thick BBO crystal (After which, the separation of wavepackets between H(o)- and V(e)-polarized light is about 580 mm) and Because the coherent length of the wavepacket is about 150 μm (4 nm FWHM interference filter is inserted before each detector), Photon 1 is prepared in the maximally mixed state. Then it sent into Mach-Zender interferometer (Fig. 3). There are two quartz crystals in the upper and lower arms respectively. The two short ones (l1) separate H(o)- and V(e)-polarized light 190° (about 150 μm), and the two longer ones (l2) separate H(o)- and V(e)-polarized light 398° (about 310 μm). The angles of their optical axes relative to horizontal plane are a, b, a’, b’ (see Fig. 3). Then beams from the two arms interact at the second beam splitter, and photon 1 is detected by single photon detector below interferometer.

\[ \langle a_{i}|b_{j}\rangle|a_{i}\rangle\langle b_{j}| = \cos a|H\rangle + \sin a|V\rangle, \langle a_{e}| = -\sin a|H\rangle + \cos a|V\rangle, \langle b_{o}| = \cos b|H\rangle + \sin b|V\rangle, \langle b_{e}| = -\sin b|H\rangle + \cos b|V\rangle \]
The visibility is always more than 50% (Fig. 4a); 2), by adjusting the angles (by using a coincidence counter (EG&G, TAC/SCA). Two detectors are coincided within a 5 ns channel.

FIG. 4: The experimental results of interference of quantum channel. We choose the visibility of interference of different quantum channels. 1), the maps according to quantum channel are changed by the range of four quartz crystals. We will observe the visibility of interference of different quantum channels. 2), We choose the visibility of any input state. Our further work will demonstrate the visibility of QKD scheme when the common quantum channel between two unbalanced Mach–Zender interferometers is not identity.

In summary, we have demonstrated the interference of quantum channels single photon Mach-Zender interferometer. Our results present the information inaccessible to the technology of quantum process tomography. This work can lead to further investigation into the phase between operations and structure and geometry of the CP maps.

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