Single-photon two-qubit entangled states: Preparation and measurement

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Abstract: We implement experimentally a deterministic method to prepare and measure single-photon two-qubit entangled states, in which the polarization and the spatial modes of a single-photon each represent a quantum bit. All four single-photon Bell-states can be easily prepared and measured deterministically using linear optical elements alone.

OCIS codes: (270.0270) Quantum optics; (999.9999) Quantum cryptography

Entanglement usually refers to multi-particle quantum entanglement which exhibits non-local quantum correlations that are verified by observing multi-particle quantum interference. A different type of "entanglement", namely "single-particle entanglement" or "entanglement" of internal degrees of freedom of a single quantum particle started to attract interest recently and it has been shown to be useful for simulating certain quantum algorithms at the expense of exponential increase of required physical resources [1, 2, 3]. It has also been shown that single-photon two-qubit states can be used for deterministic quantum cryptography [4].

For single-photon two-qubit states, two dichotomic variables of a single-photon represent the two qubits. Usually, one is the polarization qubit (e.g., horizontal $|H\rangle$ or vertical $|V\rangle$ polarization states) and the other is the spatial qubit (e.g., the photon travels in path a or in path b) [1, 3, 4]. A complete basis for the single-photon two-qubit state can be formed by a set of any four orthonormal states of the photon. For example, a set of $|a, V\rangle$, $|a, H\rangle$, $|b, V\rangle$, and $|b, H\rangle$ forms a complete (product) basis for the single-photon two-qubit Hilbert space. Preparation and measurement of such (product) basis states are trivial. In the entangled basis of the single-photon two-qubit state, the single-photon Bell-states $|\Psi^{(\pm)}\rangle \equiv \frac{1}{\sqrt{2}}(|a, H\rangle \pm |b, V\rangle)$, and $|\Phi^{(\pm)}\rangle \equiv \frac{1}{\sqrt{2}}(|a, V\rangle \pm |b, H\rangle)$ form a complete basis. In this paper, we propose a deterministic method to prepare and measure the "single-photon Bell-states" and report results on the experimental implementation of the method [6].

The outline of the experimental setup is shown in Fig. 1. Let us first focus on the state preparation part shown in Fig. 1(a). The single-photon state used in this experiment was generated using the post-selection method [5]. A 2 mm thick type-II BBO crystal was pumped with a 351.1 nm argon laser. Orthogonally polarized spontaneous parametric down-conversion (SPDC) photon pairs generated in the crystal had central wavelength of 702.2 nm and propagated collinearly with the pump beam. After removing the pump laser beam with a dichroic mirror M1, the vertically polarized photon was directed to the trigger detector T by a polarizing beamsplitter PBS and the trigger signal indicated that there was one and only one photon (polarized horizontally) traveling in the other output ports of PBS.

A half-wave plate HWP rotated the polarization of the horizontally polarized single-photon to 45° polarization state just before the second PBS. After the second PBS, the state of the single-photon can be written as $|\Psi^{(+)}\rangle = (|a, H\rangle + |b, V\rangle)/\sqrt{2}$, which is a single-photon Bell-state. The other three single-photon Bell-states can be prepared by using an additional phase shifter ϕ and polarization rotating half-wave plates θ_a and θ_b. Therefore, all four single-photon Bell-states can be easily prepared in this setup by suitable combinations of the spatial phases and polarization flip. Since all the phase and polarization adjusting components in this setup can be replaced with electro-optical devices, automated random switching among different states is possible.

Let us now discuss the measurement of single-photon Bell-states. A complete measurement of two-photon polarization Bell-states requires both nonlinear optical effects and quantum interference. On the other hand, a complete measurement of the single-photon Bell-states require only single-photon interference effects and linear optical elements. It is because entangling or interacting two separate photons requires nonlinear optical elements, but "entangling-unentangling" single-photon two-qubit states require only linear optical elements.

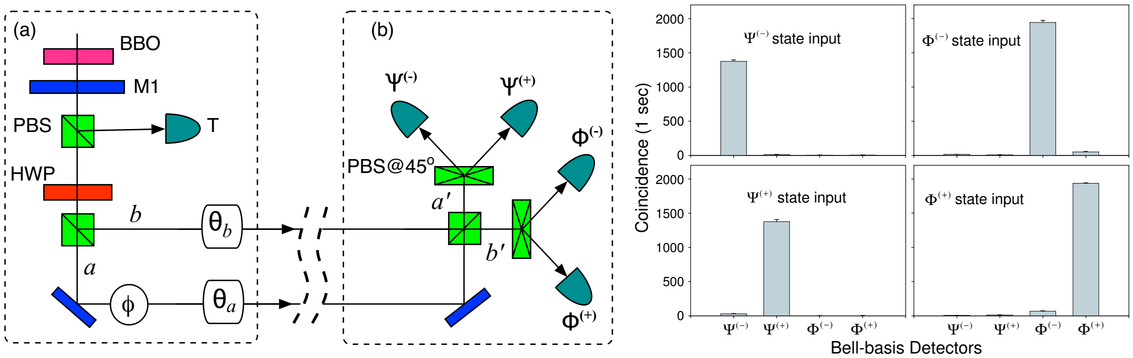

Fig. 1. Left: Outline of the experiment. (a) Preparation of a single-photon two-qubit entangled state. (b) Bell-basis measurement. The detector click at the outputs of 45° oriented PBS' uniquely identify four single-photon Bell-states. Right: Experimental data. Errors are due to imperfect alignment and phase instabilities. $|\Psi^{(\pm)}\rangle$ detectors show lower count rates than $|\Phi^{(\pm)}\rangle$ detectors due to lower photon coupling efficiencies.

The single-photon two-qubit Bell-basis measurement scheme is shown in Fig. 1(b). First, we mix the spatial qubit modes, labeled as a and b, at a polarizing beamsplitter. Since the single-photon Bell-basis detector relies on the single-photon interference effect, it is necessary that the paths a and b are kept equal. The polarizing beamsplitter transforms the incident amplitudes in the following way: $|a,H\rangle \to |a',H\rangle$, $|b,V\rangle \to |a',V\rangle$, $|b,H\rangle \to |b',H\rangle$, $|a,V\rangle \to |b',V\rangle$. The single-photon Bell-states are then transformed by the polarization beamsplitter,

$$\begin{aligned} |\Psi^{(\pm)}\rangle &\to \frac{1}{\sqrt{2}}|a'\rangle(|H\rangle \pm |V\rangle) = \begin{cases} |a'\rangle|+45^\circ\rangle \\ |a'\rangle|-45^\circ\rangle \end{cases}, \\ |\Phi^{(\pm)}\rangle &\to \frac{1}{\sqrt{2}}|b'\rangle(|V\rangle \pm |H\rangle) = \begin{cases} |b'\rangle|+45^\circ\rangle \\ -|b'\rangle|-45^\circ\rangle \end{cases}. \end{aligned}$$

Clearly, a 45° oriented polarizing beamsplitter (PBS@45°) inserted at modes a' and b' can separate the above states into four distinct spatial modes. The four single-photon detectors placed at the output ports of PBS@45°, shown in Fig. 1(b), therefore produce an unambiguous signal which corresponds to the input single-photon Bell-state.

We have implemented experimentally the preparation and measurement scheme for the single-photon Bell-states. The experimental data are shown in the right column of Fig. 1. In this experiment, the coincidence counts between the trigger detector T and four Bell-basis detectors are measured so the dark counts of individual detectors did not show up in the data. Similar reduction of dark counts can be expected in real-world situations as well, if the single-photon source is pulsed and the Bell-basis detectors are gated accordingly.

Preparation of symmetric and antisymmetric superposition states required for deterministic quantum cryptography proposed in Ref. [4] will be discussed and some practical issues on building such a system will be discussed as well [6].

The Oak Ridge National Laboratory is managed for the U.S. DOE by UT-Battelle, LLC, under contract No. DE-AC05-00OR22725.

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