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

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Entanglement often refers to multi-particle quantum entanglement which exhibits non-local quantum correlations that are verified experimentally by observing multi-particle quantum interference(1). Such quantum states and interference effects have recently been shown to be essential for new quantum applications, such as quantum information processing, metrology, lithography, etc(2). 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(3). Although single-particle entanglement lacks non-locality which is at the heart of multi-particle entanglement necessary for a number of quantum applications mentioned above, it has been shown to be useful for simulating certain quantum algorithms at the expense of exponential increase of required physical resources. It has also been shown that single-photon two-qubit states may be used for deterministic 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 in which the basis states are the orthogonal polarization states of the single-photon (e.g., horizontal $|H\rangle$ or vertical $|V\rangle$ polarization states) and the other is the spatial qubit in which the basis states are two spatial modes of the single-photon (e.g., the photon travels in path a or in path b). Clearly, 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 since interference is not required in both preparation and measurement stages. In the entangled basis of the single-photon two-qubit state, the single-photon Bell-states

$$|\Psi^{(\pm)}\rangle = \frac{1}{\sqrt{2}}(|a,H\rangle \pm |b,V\rangle),$$

$$|\Phi^{(\pm)}\rangle = \frac{1}{\sqrt{2}}(|a,V\rangle \pm |b,H\rangle),$$

form a complete basis.

In this paper, we propose a deterministic method to prepare and measure the ''single-photon Bell-states,'' report results on the experimental implementation of the method, and discuss some potential difficulties related to recently proposed single-photon two-qubit quantum cryptography scheme.

The single-photon state used in this experiment was generated using the post-selection method first demonstrated in Ref.(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, the vertically polarized photon was directed to the trigger detector 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 the PBS. A half-wave plate orieinted at 22.5° 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

$$|\Psi^{(+)}\rangle = \frac{1}{\sqrt{2}}(|a, H\rangle + |b, V\rangle),$$

which is a single-photon Bell-state. The other three single-photon Bell-states can be prepared by using an additional phase shifter and polarization rotating half-wave plates in path a and b. This method therefore allows preparation of various single-photon two-qubit states, as required for recently proposed deterministic quantum cryptography.

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. In short, complete single-photon two-qubit Bell-basis measurement can be accomplished by, first, mixing the spatial qubit modes with a PBS, and then analyzing the output ports of this PBS with four additional PBS in the 45° rotated basis.

We have implemented experimentally the preparation and measurement schemes for the single-photon Bell states(6) and have verified that the schemes proposed here are able to produce high quality single-photon Bell states in a deterministic fashon. Therefore, the schemes demonstrated here are suitable for implementing deterministic quantum cryptography protocol proposed in Ref.(4).

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