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Physics Letters A 343 (2005) 8–11
PHYSICS LETTERS A
www.elsevier.com/locate/pla

Complete Bell-states analysis using hyper-entanglement

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Received 19 May 2005; received in revised form 26 May 2005; accepted 29 May 2005

Available online 4 June 2005

Communicated by P.R. Holland

Abstract

Entanglement of energy–time is used as an ancillary to analyze four polarization entangled Bell-states. The scheme requires only linear optics and single photon detectors, and is realizable with current technology. The overall efficiency is 50%. This Bell-states measurement scheme is useful for quantum dense coding and quantum teleportation protocols.
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PACS: 03.67.Mn; 03.65.Ud; 42.50.Dv

1. Introduction

Many quantum information schemes require entangled Bell-states as a resource. Furthermore, Bell-states measurement (BSM)—distinguishing between the four maximally entangled Bell-states—is required in quantum teleportation [1–3], quantum dense coding [4,5], entanglement swapping [1,6,7], etc. However, it is difficult to distinguish the four Bell-states completely. In fact, using only linear optics and classical communication, we cannot do a complete BSM (discriminating between all four states with 100% efficiency) [8–11]. Calsamiglia and Lutkenhaus [10] have proved that the maximum efficiency for a linear Bell-states analyzer is 50%. Some schemes [5,12–14] have been done for optical BSM that allow one to distinguish two of the four Bell-states. All these schemes use local or nonlocal two-photon interference effects at beam splitters. Weinfurther has proposed a BSM method using momentum-entangled photons that allows one to distinguish all four Bell-states with 25% efficiency [12]. It is also possible to do complete BSM using nonlinear optical process [15,16] or two-photon absorption [17,18] with low efficiency.

In recent years, the interest in hyper-entanglement assisted BSM is steadily growing for its promise to perform a complete BSM utilizing entanglement in additional auxiliary degrees of freedom. We say a system is hyper-entangled when this system is entangled in two or more degrees of freedom. Due to this enlarged Hilbert space, this type of complete BSM

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doi:10.1016/j.physleta.2005.05.074

is not restricted to the efficiency limits presented in Refs. [8–11]. Kwiat and Weimfurter [19] have proposed a scheme using photons entangled in polarization and momentum, while detectors sensitive to the photon numbers are needed. Some other schemes have also been proposed by Walborn and his co-workers [20,21].

In this Letter, we present a new method for complete BSM using photon pairs which are entangled in polarization and energy–time simultaneously. In other words, the photon pairs are hyper-entangled in polarization and energy–time. Compared with previous protocols, our scheme only need linear optics and single photon detectors, and is realizable with current technology. It can be used in quantum teleportation and quantum dense coding schemes.

2. Bell-states analysis using hyper-entanglement

In the basis defined by linear horizontal (H) and linear vertical (V) polarization, the polarization entangled Bell-states are

$$\left|\Psi^{\pm}\right\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle_1|V\rangle_2 \pm |V\rangle_1|H\rangle_2\right),$$
$$\left|\Phi^{\pm}\right\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle_1|H\rangle_2 \pm |V\rangle_1|V\rangle_2\right), \tag{1}$$

where $|\sigma\rangle_j$ stand for the polarization state of the photon j. Polarization entangled photon pairs can be generated from spontaneous parametric down conversion (SPDC). The down-converted photon pairs from SPDC can be entangled in polarization. Usually the generated photon pairs from type-I two crystal source [22] are in the state

$$|\psi\rangle = \alpha|H\rangle_1|H\rangle_2 + \beta|V\rangle_1|V\rangle_2, \tag{2}$$

where α, β are complex numbers that satisfy $|\alpha|^2 + |\beta|^2 = 1$. α and β can be modified by controlling the polarization state of pump beam. We can switch $|\psi\rangle$ between the four polarization Bell states using half- and quarter-wave plates in the signal or idler path [23].

In addition, energy–time entangled states can be generated as photon pairs from SPDC passing though two unbalanced interferometers [24–28]. For each interferometer, a phase vector can be defined, e.g., the relative phase between the short (s)-long (l), path lengths. Coincidence measurement at the outputs of the interferometers can project the photon pairs into some defined entangled states when they take the same arm in each interferometer, short–short, or long–long at signal-idler path. For this type of experiments, the following conditions must be satisfied [24,28]: the coherence length of the down-converted photons is much smaller than the path-length difference in the interferometers so that no single photon interference effects are observed in passing the interferometers; the coherence length of the pump laser is much greater than these path-length differences so that we have no timing information to the creation time of the photon pairs and hence which path was taken before detection.

Consider the case that the photons take the same path in each interferometer, the state can be written as:

$$|\phi\rangle \propto c_s|s\rangle_1|s\rangle_2 + c_l e^{i(\alpha_l+\beta_l)}|l\rangle_1|l\rangle_2, \tag{3}$$

where α_l, β_l represent the phase in long interferometer arms of signal and idler path. Apparently, we can justify the state of Eq. (1) to:

$$\begin{aligned}\left|\phi^{\pm}\right\rangle &= \frac{1}{\sqrt{2}}\left(|s\rangle_1|s\rangle_2 \pm |l\rangle_1|l\rangle_2\right) \\ &= \frac{1}{\sqrt{2}}\left(|a\rangle_1|a\rangle_2 \pm |b\rangle_1|b\rangle_2\right),\end{aligned} \tag{4}$$

which are two of energy–time entangled Bell-states [27,28]. (We use symbol a, b to substitute symbol s, l for the sake of simplification.) The other two energy–time entangled Bell-states are

$$\left|\psi^{\pm}\right\rangle = \frac{1}{\sqrt{2}}\left(|a\rangle_1|b\rangle_2 \pm |b\rangle_1|a\rangle_2\right). \tag{5}$$

First, we will show how to use $|\phi^+\rangle$ as an ancillary to analyze the four polarization entangled Bell-states. The states we will work with are $\frac{1}{2}((|Ha\rangle_1|Va\rangle_2 + |Hb\rangle_1|Vb\rangle_2) \pm (|Va\rangle_1|Ha\rangle_2 + |Vb\rangle_1|Hb\rangle_2))$ and $\frac{1}{2}((|Ha\rangle_1|Ha\rangle_2 + |Hb\rangle_1|Hb\rangle_2) \pm (|Va\rangle_1|Va\rangle_2 + |Vb\rangle_1|Vb\rangle_2))$, where $|\sigma\varsigma\rangle_i$ represent the polarization and mode state of the photon i. For the sake of simplification, we rewrote these states as $|\Pi\rangle \otimes |\phi^+\rangle$, where $|\Pi\rangle$ is one of the polarization entangled Bell-states. This kind of states can be generated using the experimental set-up of Fig. 1. By post-selecting the photon pairs which arrived the detectors at the same time, we can get this type of polarization and energy–time hyper-entangled states. The efficiency to gain

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