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# Simple Scheme for Preparation of Six-photon Entangled States via Cross-Kerr Medium

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**Abstract**: A scheme is presented for preparing maximally entangled states among six modes. The scheme only utilizes weak cross-Kerr nonlinearity and momentum quadrature homodyne measurements on the probe mode of intense coherent light fields. It is relatively easy to generate Dicke states and $W$ states of light fields in the scheme. It is not necessary that the cross-Kerr nonlinearity is very large, as long as the coherent light is bright enough. Therefore, this scheme is within the reach of current technology. In addition, only weak coherent light beams, with which single-photon sources have been replaced in the signal modes, are needed in the present scheme since it is difficult to realize single-photon sources in experiments.

**Key words**: Cross-Kerr nonlinearity; Homodyne measurement; Entangled state
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## 0 Introduction

Entanglement in bipartite quantum systems is well understood and can be easily quantified. In contrast, multipartite quantum systems offer a much richer structure and various types of entanglement, and may play an important role in quantum computation and communication network[1]. Thus, crucial questions are how strongly and, in particular, in which way a quantum state can be realized entanglement. Therefore, different classifications of multipartite entanglement have been developed[2-4]. So far, many experimental schemes have focused on the observation of graph states, the Greenberger-Horne-Zeilinger (GHZ) states or the cluster states, e. g. useful for one-way quantum computation[5]. Dicke states form another important group of states, which were first investigated with respect to light emission from a cloud of atoms and have now come into the focus of both experimental realizations[3] and theoretical studies[6]. $W$ states, as a subgroup of the Dicke states, first received attention triggered by the seminal work[7] on three-qubit classification based on stochastic local operations and classical communication (SLOCC). Particularly, by applying projective measurements on a few of their qubits, states of different SLOCC entanglement classes are obtained[3,6]. These Dicke states can act as a rich resource of multipartite entanglement as required for quantum information applications.

The advantage of using photons is that single-qubit operations can be implemented with high precision. In addition, as information carriers in quantum computing [8], photonic qubits have the advantage of undergoing negligible decoherence. In addition, the advantage of using photons is that single-qubit operations can be implemented with high precision. However, the absence of any significant photon - photon interaction is problematic for the realization of non-trivial two-qubit gates[9]. This problem has been overcome by cross-phase modulation (XPM)[10], which refers to the nonlinear phenomenon that the phase of an optical field is modulated by another field[11-12].

Wieczorek et. al. experimentally observed the six-photon polarization-entangled Dicke state using the second-order emission process of collinear type-II spontaneous parametric down conversion (SPDC)[13]. In this paper, we present an alternative approach for preparing Dicke states, and incidentally $W$ states, is to utilize the weak cross-Kerr nonlinearity combined with a strong probe coherent field. This scheme only requires the cross-Kerr nonlinear interaction between light

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fields in coherent states and beam splitters (BS), followed by a homodyne measurement. Stockton et. al. considered that Dicke state is difficult to reliably produce from an initially unentangled state[14]. However, we have proposed the simple and efficient scheme in which it's comparatively easy to realize highly symmetric entangled Dicke states of light fields.

## 1 Entangled among six modes

Before we begin our detailed discussion on the preparation scheme, let briefly review the useful weak cross-Kerr nonlinearity which has been used in Refs.[10, 15-16]. Suppose a nonlinear weak cross-Kerr interaction between a signal mode initially in a superposition of photon-number states $|\varphi\rangle_s = c_0|0\rangle_s + c_1|1\rangle_s + c_2|2\rangle_s$ and a probe mode initially in a coherent state $|\alpha\rangle_p$. The cross-Kerr interaction causes the combined signal-probe system to evolve as

$$|\varphi\rangle_s \otimes |\alpha\rangle_p \rightarrow c_0|0\rangle_s|\alpha\rangle_p + c_1|1\rangle_s|\alpha e^{i\theta}\rangle_p + c_2|2\rangle_s|\alpha e^{i2\theta}\rangle_p \quad (1)$$

where $\theta$ is induced by the nonlinearity. Conditioned on the results of QND measurement like Ref. [15], the signal state will be projected into a definite number state or superposition of number states with high fidelity.

Now let us study the generation of the entangled states among four modes, e. g., Dicke states and $W$ states. The scheme is shown in Fig. 1, where $BS_i$ is beam splitter, $\theta_i$ is Kerr medium, M is mirror, and HD is a homodyne detector.

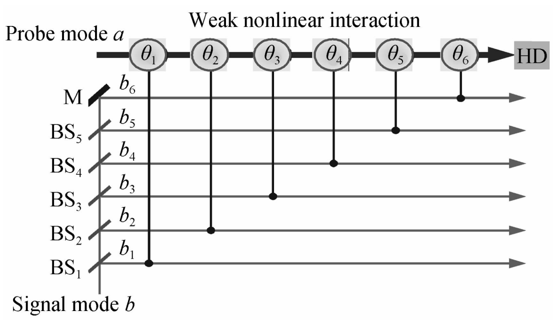


Fig. 1 Schematic setup

In a homodyne detection using XPM based on optical Kerr effect, a coherent light beam is split into two, one of which is referred to as the probe" and the other as the "reference". The probe is coupled to a "signal" beam in cross-Kerr medium which induces a phase shift on the probe proportional to the intensity of the signal. This phase shift is measured by an optical interferometer, formed by recombining the probe and the reference at a symmetric balanced BS[10]. $BS_1$ has the reflection/transmission($r_1$) = 1/5 and $BS_2$ has the $r_2 = 1/4$ and $BS_3$ has the $r_3 = 1/3$ and $BS_4$ has the $r_4 = 1/2$ and $BS_5$ has the $r_5 = 1/1$, so that the signal modes $b_1$, $b_2$, …, $b_5$ and $b_6$ have same strength, and we assume all of them to be in the weak coherent state $|\beta\rangle$ ($|\beta| \langle\langle 1$). Because $|\beta\rangle_j$ ($j = 1, 2, \cdots, 6$) is weak, $|\beta\rangle_j \approx (1/\sqrt{1+\beta^2})(|0\rangle + \beta|1\rangle)_j$, where $|0\rangle$ and $|1\rangle$ are the vacuum state and one-photon state, respectively. Only weak coherent light beams, with which single-photon sources have been replaced in the signal modes, are needed in the present scheme since it is difficult to realize single-photon sources in experiments. Assume that the probe mode a is in a coherent state $|\alpha\rangle$. Mode a and modes $b_j$ interact at the Kerr mediums $\theta_1$, $\theta_2$, …, $\theta_6$, respectively, which is described by Eq. (1). And for simplicity, set the scaled interaction intensity $\theta$ being the same in Kerr mediums, that is, $\theta_j = \theta$. The process of preparation of six-photon entangled states can be described by

$$\begin{aligned}
|\Psi_{in}\rangle = &|\beta\rangle_6 \otimes |\beta\rangle_5 \otimes \cdots \otimes |\beta\rangle_1 \otimes |\alpha\rangle \rightarrow \\
|\Psi\rangle = &\frac{1}{(1+|\beta|^2)^3}[|0^{\otimes 6}\rangle_{654321}|\alpha\rangle + \\
&\beta(\sum_l P_l|10^{\otimes 5}\rangle)_{654321}|\alpha e^{i\theta}\rangle + \\
&\beta^2(\sum_l P_l|1^{\otimes 2}0^{\otimes 4}\rangle)_{654321}|\alpha e^{i2\theta}\rangle + \\
&\beta^3(\sum_l P_l|1^{\otimes 3}0^{\otimes 3}\rangle)_{654321}|\alpha e^{i3\theta}\rangle + \\
&\beta^4(\sum_l P_l|1^{\otimes 4}0^{\otimes 2}\rangle)_{654321}|\alpha e^{i4\theta}\rangle + \\
&\beta^5(\sum_l P_l|1^{\otimes 5}0\rangle)_{654321}|\alpha e^{i5\theta}\rangle + \\
&\beta^6|1^{\otimes 6}\rangle_{654321}|\alpha e^{i6\theta}\rangle]
\end{aligned} \quad (2)$$

where the subscripts 1, 2, …, 6 denote modes $b_1$, $b_2$, …, $b_6$, respectively. $\sum_l P_l(\cdots)$ means the sum over all permutations in the usual notation of encoded logical photonic qubits in Eq. (2).

Strong probe mode interacts successively with multiple signal-mode photons, each causing a conditional phase rotation in the probe mode. Subsequent $P$-quadrature ($P$: momentum) homodyne measurement[15], as quantum scissors, of the probe mode will project the photons in the signal mode into the desired entangled states. The scheme uses $P$-quadrature homodyne measurement, which requires considerably smaller strength of the coherent state in the probe mode than the $X$-quadrature ($X$: position) homodyne measurement in other schemes[12]. For the convenience of the analysis of the subsequent $P$-quadrature homodyne measurement on the strong probe mode, the state can be expanded in terms of the eigenstates of the $\hat{p}$ operator:

$$\langle\Psi\rangle=\int|p\rangle\langle p|\Psi\rangle\mathrm{d}p=\int\Psi_{\mathrm{p}}|p\rangle\mathrm{d}p,$$

$$\begin{aligned}\Psi_{\mathrm{p}}=N(&g_0\mathrm{e}^{\mathrm{i}\tau_0}|0^{\otimes 6}\rangle_{654321}+\beta g_1\mathrm{e}^{\mathrm{i}\tau_1}\sqrt{C_6^1}|D_6^{(1)}\rangle+\\&\beta^2 g_2\mathrm{e}^{\mathrm{i}\tau_2}\sqrt{C_6^2}|D_6^{(2)}\rangle+\beta^3 g_3\mathrm{e}^{\mathrm{i}\tau_3}\sqrt{C_6^3}|D_6^{(3)}\rangle+\\&\beta^4 g_4\mathrm{e}^{\mathrm{i}\tau_4}\sqrt{C_6^4}|D_6^{(4)}\rangle+\beta^5 g_5\mathrm{e}^{\mathrm{i}\tau_5}\sqrt{C_6^5}|D_6^{(5)}\rangle+\\&\beta^6 g_6\mathrm{e}^{\mathrm{i}\tau_6}|1^{\otimes 6}\rangle_{654321})\end{aligned}\quad(3)$$

Here the coefficients are

$$g_n=\pi^{-1/4-(p-\sqrt{2}\alpha\sin n\theta)^2/2}\quad(4)$$

$$\tau_n=\sqrt{2}\alpha(p-\frac{1}{\sqrt{2}}\sin n\theta)\cos n\theta\quad(5)$$

$$N=(\sum_{n=0}^{6}C_6^n\beta^{2n}g_n^2)^{-1/2}\quad(6)$$

where $n=0, 1, \cdots, 6$, and

$$|D_6^{(1)}\rangle=(C_6^1)^{-1/2}(\sum_l P_l|10^{\otimes 5}\rangle)_{654321}=|W_6^{(1)}\rangle\quad(7)$$

$$|D_6^{(2)}\rangle=(C_6^2)^{-1/2}(\sum_l P_l|1^{\otimes 2}0^{\otimes 4}\rangle)_{654321}\quad(8)$$

$$|D_6^{(3)}\rangle=(C_6^3)^{-1/2}(\sum_l P_l|1^{\otimes 3}0^{\otimes 3}\rangle)_{654321}\quad(9)$$

$$|D_6^{(4)}\rangle=(C_6^4)^{-1/2}(\sum_l P_l|1^{\otimes 4}0^{\otimes 2}\rangle)_{654321}\quad(10)$$

$$|D_6^{(5)}\rangle=(C_6^5)^{-1/2}(\sum_l P_l|1^{\otimes 5}0\rangle)_{654321}=|W_6^{(5)}\rangle\quad(11)$$

Here $(C_n^k)^{-1/2}$ is a normalization factor with $C_n^k$ as binomial coefficient in the Eqs. (7)～(11). Eqs. (7)～(11) can be named as Dicke states $|D_n^{(l)}\rangle$[13]. For example, Eqs. (7) and (8) can be named as 6-qubit 1-excitation $W$ state and 6-qubit 2-excitation Dicke state, respectively.

In Fig. 2, we plot $\sqrt{C_6^n}\beta^n g_n$ which are the Gaussian functions of the homodyne measurement result $p$. We observe that $\sqrt{C_6^n}\beta^n g_n$ are five Gaussian curves with the peaks located at $\sqrt{2}\alpha\sin n\theta$, respectively. The neighboring peaks are separated by the distances $2d_n=\sqrt{2}\alpha\{\sin(n\theta)-\sin[(n-1)\theta]\}$, which are referred to as the distinguishabilities of

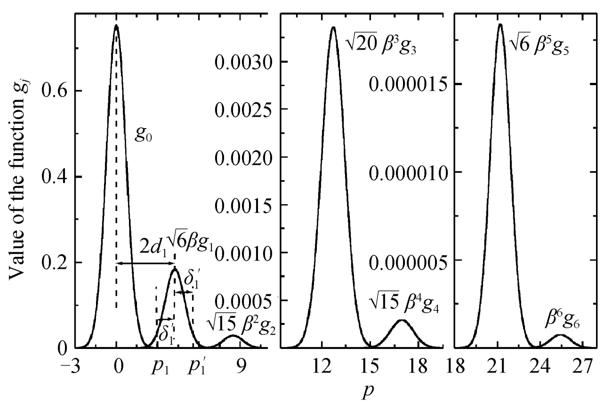


Fig. 2 Curves of the homodyne measurement result $p$ with $\alpha=300$, $\theta=0.01$ and $\beta=0.1$

the measurement. Since the distinguishabilities are approximately in proportion to $\alpha\theta$ when $\theta\ll 1$, we can use a strong coherent state probe light to ensure good distinguishability which make the overlaps between these curves very small. However, the distinguishabilities in Ref. [12] are approximately in proportion to $\alpha\theta^2$. As we have shown, as long as the probe beam has a sufficient amplitude $\alpha$, we can work with much smaller phase shifts. This makes our distinguishability rather easier to implement.

The $P$ homodyne measurement, which is near the center of one of the peaks, is subsequently implemented on the probe beam. Suppose, for example, the result is $p_1=\sqrt{2}\alpha\sin(\theta)-\delta_1$, which is near the peak of $\sqrt{6}\beta g_1$ as seen from Fig. 2. In this case, the polarization photon state in Eq. (3) is very close to the entangled state $|W_6^{(1)}\rangle$. The fidelity of the resulting state with respect to $|W_6^{(1)}\rangle$ is

$$F_{|W_6^{(1)}\rangle}(p_1)=|\langle W_6^{(1)}|\Psi_{\mathrm{p}}\rangle|\approx\left(\frac{1}{1+\frac{1}{6\beta^2}\mathrm{e}^{-4d_1(d_1-\delta_1)}}\right)^{1/2}\quad(12)$$

For given $\beta$, $\alpha$ and $\theta$, we can decide $\delta_1$ from the needed high fidelity. Assuming that $\beta=0.1$, $\theta=0.01$ and $\alpha=400$, $F_{|W_6^{(1)}\rangle}(p_1)$ will be 0.9999 with $\delta_1\approx 0.645d_1$. Similarly, if the measurement result is $p_1'=\delta_1'+\sqrt{2}\alpha\sin\theta$, the resulting fidelity with respect to $|W_6^{(1)}\rangle$ will be

$$F_{|W_6^{(1)}\rangle}(p_1')\approx(\frac{1}{1+2.5\beta^2\mathrm{e}^{-4d_2(d_2-\delta_1')}})^{1/2}\quad(13)$$

Assume the minimal acceptable fidelity of the resulting state is $F_{\min}$. By appropriately choosing $\delta_1$ and $\delta_1'$, we can have $F_{|W_6^{(1)}\rangle}(p_1)=F_{|W_6^{(1)}\rangle}(p_1')=F_{\min}$. Then, as long as the measurement result $p$ is in the regime of $p_1<p<p_1'$, we can get the polarization photon state $|W_6^{(1)}\rangle$ with the fidelity higher than $F_{\min}$. The probability of such an event that is close to the polarization entangled state $|W_6^{(1)}\rangle$ is

$$P=\int_{p_1}^{p_1'}\langle p|\mathrm{tr_{si}}(|\Psi\rangle\langle\Psi|)|p\rangle\mathrm{d}p\approx\frac{3|\beta|^2}{(1+|\beta|^2)^6}[\mathrm{erf}(\delta_1)+\mathrm{erf}(\delta_1')]\quad(14)$$

As the distinguishabilities increase, this success probability of obtaining the $W$ state will approach $6|\beta|^2/(1+|\beta|^2)^6$. The $W$ state has been used to realize the teleportation of an unknown state probability. In addition to the $W$ states among six modes, plentiful new kinds of entangled states can be generated with this scheme, e. g. highly symmetric Dicke state. GHZ and $W$ class states cannot be transformed into one another via SLOCC and not even by entanglement catalysis. However, Dicke state can be projected into both classes by a local operation. Similar analysis can be made to obtain the state $|D_6^{(2)}\rangle$, $|D_6^{(3)}\rangle$, $|D_6^{(4)}\rangle$ and $|W_6^{(5)}\rangle$ with the desired fidelity and the corresponding success probability $15|\beta|^4/(1+|\beta|^2)^6$, $20|\beta|^6/(1+|\beta|^2)^6$, $15|\beta|^8/(1+|\beta|^2)^6$ and $6|\beta|^2/(1+|\beta|^2)^6$ when the measurement result $p$ is near the centers of the $\sqrt{C_6^n}\beta^n g_n$ with $n=2,3,\cdots,6$ in Fig. 2, respectively.

To realize the necessary 20 permutations, three vacuum states and three one-photon states in a single mode are distributed by nonpolarization-independent beam splitters into six modes for $|D_6^{(3)}\rangle$, which is a symmetric six-qubit Dicke state with three excitations. In Ref. [13], they focus on the symmetric six-qubit Dicke state with three excitations of polarized photons in their experiments. The state is of considerable interest for applications in quantum information processing (QIP) and precision metrology. The Dicke state, just like $W$ state, is highly persistent against photon loss and projective measurements. In Ref. [7], it was shown that, in particular, in spite of the impossibility to transform a three-photon GHZ type into a $W$ state by local manipulation, both can be obtained via a projective measurement of the same photon in the four-photon Dicke state. Multipartite entangled states, such as Dicke states and $W$ states, can be useful for important QIP tasks. For Dicke states, quantum telecloning, quantum secret sharing, open-destination teleportation and quantum games [17] have been mentioned. For $W$-class states, quantum teleportation, dense coding, quantum key distribution [18], have been proposed.

This adjustable cascaded scheme can be seen as a continuation of experiments on $|D_2^{(1)}\rangle$ [19] and $|D_4^{(2)}\rangle$ [3] and $|D_6^{(3)}\rangle$ [13, 20] and obviously can be extended to higher even photon numbers.

## 2 Conclusion

In conclusion, the scheme is presented for preparing mutliphoton entangled states based on weak cross-Kerr nonlinearity. Two coherent fields interact when they enter a nonlinear cross-Kerr medium. It is clear that the feasibility of the present schemes depends on the veracity in the homodyne measurement and the implementation of cross-Kerr nonlinearity. Analysis of the veracity in the momentum quadrature homodyne measurement is presented [21]. The scheme of the present paper has some similar features with that of Ref. [15] in using such small-but-not-tiny Kerr nonlinearities. Schmidt and Imamoĝlu [22] suggested originally that the giant crossed-Kerr nonlinearity can also be achieved by utilizing the extremely slow group velocity which is obtained as a consequence of electromagnetically induced transparency. Harris and Hau [23], developing the suggestions of Ref. [22], showed that, when the ultraslow group velocity is the dominant feature of the problem, nonlinear optical processes between traveling pulses with a low number of photons become feasible. A conditional phase shift 16° per photon has been measured in the experiment of Ref. [24] which involved two frequency-distinct cavity modes in a high-finesse cavity. However, it is not necessary in the present scheme that the cross-Kerr nonlinearity is very large as long as the coherent light is bright enough. In addition, there are some differences between them; the main difference is that single-photon sources are needed in Ref. [25] while only coherent light beams are needed in our scheme. Considering that single-photon sources are difficult to realize in experiments while the coherent light source is an ordinary one, it has some advantages to replace single-photon sources with coherent light beams. These make us more confident on the feasibility of the proposed scheme. Compared with the already existing optical schemes for preparation of Dicke states in Refs. [3, 13, 20], our work has several advantages: (i) This is a very simple scheme proposing to produce entangled Dicke states of many photonic modes with the help of cross-Kerr nonlinearity and homodyne detection. (ii) This approach takes advantage of the homodyne measurement which can be made much more efficient than the single-photon detection. Photon loss for the signal modes can be treated efficiently through 'indirect measurements'. The key advantage with homodyne measurement is that it is near perfect fidelity for preparation. (iii) Only weak coherent light beams, with which single-photon sources have been replaced in the signal modes, are needed in the present scheme since it is difficult to realize single-photon sources in experiments.

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# 利用交叉克尔效应制备六光子纠缠态

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**摘　要**：利用弱非线性的交叉克尔介质和对强相干探测场的动量积分零拍探测，呈现了一个关于制备六光子最大纠缠态的方案，如实现制备 Dicke 态和 W 态. 在本方案中，只要相干探测光场的强度足够大时，对交叉克尔介质的非线性强度要求可以较弱，因而当前实验技术条件上均能满足本方案的要求. 考虑到目前实验上实现单光子很是相对困难的，在信号模上仅用弱的相干光替代单光子源，从而进一步增强了本方案的实验可行性.

**关键词**：交叉克尔非线性；零拍探测；纠缠态