Abstract. We describe a cavity-QED scheme to deterministically generate polarization entangled photon pairs by using a single atom successively coupled to two single longitudinal mode cavities presenting polarization degeneracy. The cavities are initially prepared either in the vacuum state or in a single photon Fock state for each orthogonal polarization. Sharing the same basic elements, the source can operate on different physical processes. For a $V$-type three-level atom initially prepared in the ground state two implementations of the source are possible using either: i) two truncated Rabi Oscillations, or ii) a counterintuitive Stimulated Raman Adiabatic Passage process. Although slower than the former implementation, this second one is very efficient and robust under fluctuations of the experimental parameters and, particularly interesting, almost insensitive to atomic decay. For a four-level atom in a diamond configuration initially prepared in the upper state, the source can produce entangled photon pairs even in the bad cavity limit via an adiabatic passage process. We have performed Monte Carlo wave function simulations to characterize these sources by means of: i) the success probability $P$ of producing the desired entangled state, ii) the fidelity $F$ in the reduced space of two emitted cavity photons, and iii) the $S$ parameter of the Clauser-Horne-Shimony-Holt (CHSH) inequality to quantify the entanglement capability.

1. Introduction
Entanglement is a quantum correlation that appears in composite systems and constitutes one of the main resources for quantum applications. The present large interest in the study of entanglement is driven both by fundamental questions such as testing quantum mechanics against local hidden variables theories [1] and by practical applications, e.g., in quantum information [2]. Thus, in quantum communication, entanglement between two systems at different locations enables quantum teleportation [3] and entanglement-based quantum cryptography [4]. Entangled pairs are also essential ingredients in various proposed schemes for quantum computing [5, 6], and are needed for fast coupling of distant qubits in some promising quantum computer architectures [7, 8]. In optics, parametric down conversion (PDC) in non-linear birefringent crystals is the usual source of entangled photon pairs [9–11]. For these sources, the statistics of the number of pairs and their time distribution follows, essentially, a Poissonian distribution. This feature severely restricts the range of practical applications of PDC sources, e.g., for entanglement-based quantum cryptography protocols [4]. Accordingly, one of the practical issues in entanglement-based quantum cryptography presently attracting considerable attention is the development of light sources that emit deterministically single entangled photon pairs (named, entangled photon pair gun) at a constant rate [12–14]. Here we review several recent proposals by us for an entangled photon pair gun [15–17].

Specifically, we describe a cavity-QED scheme to deterministically generate polarization entangled photon pairs by using a single atom successively coupled to two single longitudinal mode cavities presenting polarization degeneracy. The cavities are initially prepared either in the vacuum state or in a
In what follows, we will use the following notation for the state of the full system atom plus cavity frequency two high-Q cavities both displaying polarization degeneracy and having identical longitudinal mode and the two mode cavities in the vacuum state. Section scheme is conformed by a four-level atom in a diamond configuration initially prepared in the upper state, with cavity confining two orthogonal photons and the cavity vacuum mode vacuum state of cavity. The two schemes under investigation are sketched in Fig. 1. The first scheme, Fig. 1(a), is composed of a single V-type three-level atom with two electric dipole transitions of frequencies detunings from the corresponding atomic transitions. For other details see Section 2.

The two schemes under investigation are sketched in Fig. 1. The first scheme, Fig. 1(a), is composed of a single V-type three-level atom initially prepared in the ground state, with cavity 1 confining two orthogonal photons and the cavity 2 in the vacuum state. The second scheme is conformed by a four-level atom in a diamond configuration initially prepared in the upper state and the two mode cavities in the vacuum state. Section 3 is devoted to analyse the coherent dynamics for both proposals. In Section 4 we will describe two entangling mechanisms using either: (i) two truncated Rabi Oscillations (RO) (Section 4.1), or (ii) an Stimulated Raman Adiabatic Passage (STIRAP) process (Section 4.2). In Section 5 we will consider the presence of various decoherence processes by using Monte Carlo Wave Function (MCWF) simulations. Thereby, we will characterize the feasibility of the sources by means of the success probability $P$ of producing the entangled state. In Section 6 we will calculate the fidelity $F$ of generating the entangled state $|E^\pm\rangle$ for the reduced space of two cavity-emitted photons, and quantify the entanglement capability of the source by means of the $S$ parameter of the Clauser-Horne-Shimony-Holt (CHSH) inequality. Section 7 will be devoted to analyse the influence of some practical imperfections in the source feasibility. Finally, in Section 8 we will summarize our main findings.

2. The Physical Model

The two schemes under investigation are sketched in Fig. 1. The first scheme, Fig. 1(a), is composed of a single V-type three-level atom with two electric dipole transitions of frequencies $\omega_{ac}$ and $\omega_{bc}$, and two high-Q cavities both displaying polarization degeneracy and having identical longitudinal mode frequency $\omega_c$. $\Delta_{1+} = \Delta_{2+} = \omega_c - \omega_{ac}$, and $\Delta_{1-} = \Delta_{2-} = \omega_c - \omega_{bc}$ are the corresponding detunings. In what follows, we will use the following notation for the state of the full system atom plus cavity
the following initial state of the system:

\[ |j\rangle \otimes |k, l\rangle_1 \otimes |m, n\rangle_2 \equiv |j; k, l; m, n\rangle \]  

(1)

where \( j \) denotes the atomic state \( j = a, b, c \) and \( k(m) \) and \( l(n) \) denote the number of \( \sigma_+ \) and \( \sigma_- \) polarized photons of the cavity mode 1(2). For our proposal to work, we need to prepare the first system into the following initial state:

\[ |I\rangle \equiv |c; 1, 1; 0, 0\rangle = a_{1+}^\dagger a_{1-}^\dagger |c\rangle \otimes |\Omega\rangle \]  

(2)

where \( a_{1+}^\dagger (a_{1-}^\dagger) \) is the photon creation (annihilation) operator for each mode \( i = 1, 2 \), and \( \alpha = \pm \) refers to the two circular polarizations. \( |\Omega\rangle \equiv |\Omega\rangle_1 \otimes |\Omega\rangle_2 \), being \( |\Omega\rangle_1 \) the two mode vacuum state of cavity \( i \).

Next, we will show how under the symmetric conditions above mentioned the couplings given by Eq. 4 are governed by Eq. (4) such that the system will remain in the space spanned by the five states of Fig. 2(a). For our proposal to work, we need to prepare the first system into the following initial state:

\[ |I'\rangle \equiv |0_0; 0, 0; 0, 0\rangle = |0_0\rangle \otimes |\Omega\rangle. \]  

(3)

where we use the notation \( |F_{mF}\rangle \) for the atomic state. Note that the latter initial field state is the simplest in optical cavity-QED, namely the vacuum state for all cavity modes.

3. The Coherent Dynamics

The coherent dynamics of both systems can be described by the same interaction Hamiltonian, that in the rotating wave approximation is given by \( (\hbar = 1) \):

\[ H_1 = \sum_{i=1,2} \sum_{\alpha=+,-} g_{i\alpha} \left( a_{i\alpha}^\dagger S_{i\alpha} + a_{i\alpha} S_{i\alpha}^\dagger \right), \]  

(4)

where \( g_{i\alpha} \) is the vacuum Rabi frequency of the corresponding cavity and polarization mode. \( S_+ = |c\rangle \langle a| \) and \( S_- = |c\rangle \langle b| \) are the atomic lowering operators for the first scheme, and \( S_{1+} = |1_+\rangle_1 \langle 0|_0 \), \( S_{1-} = |1_-'\rangle_1 \langle 0|_0 \), \( S_{2+} = |0_0\rangle \langle 1_+|_1 \), \( S_{2-} = |0_0\rangle \langle 1_-|_1 \) are the lowering operators for the second scheme. In what follows we will consider the completely symmetric case given by \( g_{i+}(t) = g_{i-}(t) (\equiv g_i(t)) \) for both schemes, and \( \Delta_{1+} = \Delta_{2+} = \Delta_{1-} = \Delta_{2-} (\equiv \Delta) \) for the first scheme, and \( \Delta_{1+} = \Delta_{1-} (\equiv \Delta) \), and \( \Delta_{2+} = \Delta_{2-} (\equiv \Delta_2) \) for the second one. Eventually, we will relax these conditions by considering the presence of practical imperfections such as stray electric and magnetic fields.

For the first scheme and in the absence of dissipation, the coherent evolution of the system will be governed by Eq. (4) such that the system will remain in the space spanned by the five states of Fig. 2(a). Next, we will show how under the symmetric conditions above mentioned the couplings given by Eq. 4 can be reduced to those of a three-level system. In order to show this, we will consider the following alternative basis for the first scheme:

\[ |I\rangle \equiv a_{1+}^\dagger a_{1-}^\dagger |c\rangle \otimes |\Omega\rangle, \]  

(5)

\[ \sqrt{2}|B\rangle \equiv \left( S_{1+}^\dagger a_{1-}^\dagger + S_{1-}^\dagger a_{1+}^\dagger \right) |c\rangle \otimes |\Omega\rangle, \]  

(6)

\[ \sqrt{2}|D\rangle \equiv \left( S_{1+}^\dagger a_{1-}^\dagger - S_{1-}^\dagger a_{1+}^\dagger \right) |c\rangle \otimes |\Omega\rangle, \]  

(7)

\[ \sqrt{2}|E^\pm\rangle \equiv \left( a_{2+}^\dagger a_{1-}^\dagger \pm a_{2-}^\dagger a_{1+}^\dagger \right) |c\rangle \otimes |\Omega\rangle. \]  

(8)
Therefore, the coupling chain reduces to that of a three-level system as it is schematically illustrated in Fig. 2(b).

On the other hand and concerning to the second scheme, the coherent dynamics of the system is also restricted to a five state manifold, Fig. 2(c), that reduces to that of a three-level system, Fig. 2(d), when the following basis is considered:

$|I'\rangle \equiv |0\rangle \otimes |\Omega\rangle,$  
$\sqrt{2}|B'\rangle \equiv \left(S_{1+}a^{\dagger}_{1+} + S_{1-}a^{\dagger}_{1-}\right) |I'\rangle,$  
$\sqrt{2}|D'\rangle \equiv \left(S_{1+}a^{\dagger}_{1+} - S_{1-}a^{\dagger}_{1-}\right) |I'\rangle,$  
$\sqrt{2}|E^{\pm}\rangle \equiv \left(S_{2-}a^{\dagger}_{2-}S_{1+}a^{\dagger}_{1+} \pm S_{2+}a^{\dagger}_{2+}S_{1-}a^{\dagger}_{1-}\right) |\Omega'\rangle.$

In this case and taking the interaction picture, the off-diagonal matrix elements of the Hamiltonian are:

$\langle D'|H|I'\rangle = \langle D|H|E^+\rangle = \langle B|H|E^-\rangle = 0$  
$\langle B'|H|I'\rangle = \sqrt{2}g_1 e^{-i\Delta t}$  
$\langle B'|H|E^+\rangle = \langle D|H|E^-\rangle = g_2 e^{-i\Delta t}$  
$\langle D'|H|E^+\rangle = \langle D|H|E^-\rangle = 0$  
$\langle B'|H|E^-\rangle = \sqrt{2}g_1 e^{-i\Delta t}$  
$\langle B'|H|E^+\rangle = g_2 e^{i\Delta t}$
4. Entangling Mechanisms

The fact that the coupling chain from the initial state to the desired entangled state can be reduced to that of a three-level system suggests to shape \(g_1(t)\) and \(g_2(t)\) such that the population is transferred through the intermediate state \(|B\rangle\), the two RO proposal, or directly to \(|E^+\rangle\), the STIRAP proposal. These two proposals will be analyzed along the following lines for the first scheme of Fig. 1.

4.1. The two Rabi Oscillations proposal

For the scheme of Fig. 1(a), the dynamical evolution of the system will be obtained by integrating the Schrödinger equation with the corresponding Hamiltonian. For the sake of making the discussion analytical, let us consider first that \(g_i \ (i = 1, 2)\) is constant in time and different from zero only during a time interval of duration \(t_i\). These two time intervals do not overlap and coupling occurs first in cavity 1. In this case, the system evolves in cavity 1 according to

$$|\psi(t)\rangle = e^{-i\Delta t/2} \left[ -\frac{2g_1\sqrt{2}}{\Omega_1} \sin(\Omega_1 t/2) \right] |B\rangle + e^{i\Delta t/2} \left[ i \cos(\Omega_1 t/2) - \frac{\Delta}{\Omega_1} \sin(\Omega_1 t/2) \right] |I\rangle$$

(18)

where \(\Omega_1 = \sqrt{8g_1^2 + \Delta^2}\) is the generalized Rabi frequency. From Eq.(18) it is inferred that if the single photon resonance condition is fulfilled, i.e., \(\Delta = 0\), population is completely transferred from \(|I\rangle\) to \(|B\rangle\)

if \(\Omega_1 t_1 = \pi\), i.e., whenever half of a Rabi oscillation (a \(\pi\)-pulse) between these two states takes place. In this case, the quantum state will be:

$$|\psi(t_1)\rangle = -i|B\rangle = -\frac{i}{\sqrt{2}} \left( S^+_1 a^+_1 - S^-_1 a^+_2 \right) \Omega$$

(19)

After a time \(t_f\) of free evolution, the atom interacts with the vacuum modes of cavity 2 and the system evolves according to:

$$|\psi(t)\rangle = e^{-i\Delta t'/2} \left[ -\frac{2g_2}{\Omega_2} \sin(\Omega_2 t'/2) \right] |E^+\rangle + e^{i\Delta t'/2} \left[ i \cos(\Omega_2 t'/2) + \frac{\Delta}{\Omega_2} \sin(\Omega_2 t'/2) \right] |B\rangle$$

(20)

being \(\Omega_2 = \sqrt{4g_2^2 + \Delta^2}\) the generalized Rabi frequency in the second cavity and \(t' = t - (t_1 + t_f)\). On single-photon resonance (\(\Delta = 0\)), if the interaction in the second cavity lasts a time \(t_2\) fulfilling \(\Omega_2 t_2 = \pi\), then the population will be completely transferred from \(|B\rangle\) to \(|E^+\rangle\):

$$|\psi(t_1 + t_f + t_2)\rangle = \frac{1}{\sqrt{2}} \left( a^+_2 a^+_1 - a^-_2 a^+_1 \right) |\Omega\rangle = -|E^+\rangle$$

(21)

To be more realistic, in the numerical simulations shown in Figs. 3 we have considered a gaussian profile for the atom-field interaction of the form:

$$g_i(t) = g e^{-(t-\bar{t}_i)^2/\tau_i^2} \quad \text{with} \quad i = 1, 2,$$

(22)

where \(\bar{t}_1 = t_1/2\) and \(\bar{t}_2 = t_2/2 + t_f + t_1\). \(t_i\) is the interaction time in each cavity, \(t_f\) is the delay time (or free time of flight) between the two interactions and \(\tau_i\) is the width of the corresponding gaussian profile.

Fig. 3 (b) shows, for \(\Delta = 0\), the population transfer from \(|I\rangle\) to \(|E^+\rangle\) through the two truncated Rabi oscillations. We have obtained the same results for the scheme of Fig. 1(b) whenever \(\Delta_1 = \Delta_2 = 0\).

4.2. The Stimulated Raman Adiabatic Passage proposal

The generation of entangled photon pairs can be arranged in a very different way via an adiabatic passage process that, although slower than the previous proposal, gives rise to a larger robustness against practical imperfections. In order to illustrate this proposal we will consider the first scheme of Fig. 1.
and eventually we will consider the second scheme. By diagonalizing the Hamiltonian of the V-type atom plus cavity modes in the interaction picture and assuming the two-photon resonance condition, i.e., $\Delta_1 = \Delta_2$, it results that one of the energy eigenstates of the system is:

$$|\Lambda(\theta)\rangle = \cos \theta |I\rangle - \sin \theta |E^+\rangle,$$

(23)

where the mixing angle $\theta$ is defined as $\tan \theta(t) = \sqrt{2}g_2(t)/g_1(t)$. Following Eq. (23), it is possible to transfer the system from $|I\rangle$ to $|E^+\rangle$ by adiabatically varying the mixing angle from 0 to $\pi/2$ realizing a counterintuitive STIRAP process [19] as can be seen from Fig. 3 (c-d). In this case, the steps to generate the polarization entangled photon pair are: firstly, preparation of the system into the initial state $|I\rangle$; secondly, the atom couples first to the empty modes of cavity 2; and, finally, before this interaction ends, the atom starts to slowly interact with the modes of cavity 1. Note that this last step means that the transverse spatial modes of the two cavities should appropriately overlap to assure the adiabaticity of the process as it is depicted in Fig. 3 (c). Although slower than the two truncated ROs proposal, the STIRAP process has two advantages: (i) it is very robust under fluctuations of the experimental parameters, e.g., interaction strengths and times, provided the adiabaticity condition is fulfilled; and (ii) for the scheme
under consideration, it is almost not sensitive to atomic decay since, first, there is no need of single photon resonance, and, second, $|\Lambda(\theta)\rangle$ does never involve the intermediate decaying state $|B\rangle$ as it is shown in Fig. 3 (d).

We have also applied the STIRAP proposal for the second scheme under investigation (Fig. 1(b)). Under the two-photon resonance condition $\Delta_1 = -\Delta_2$, and under the adiabaticity condition we have obtained the same results that are shown in Fig. 3(d) for the first scheme, i.e., an almost perfect population transfer from $|I^0\rangle$ to $|E^+\rangle$. Differences between the results of the two proposals for the first and the second scheme only appear when dissipation is considered. Dissipation for these two schemes will be discussed in the next section.

5. Monte Carlo Wave Function Simulations

In the previous analysis only the coherent interaction of the atom with the modes of the cavities was considered. However, a realistic study of the feasibility of the two proposals has to take into account incoherent processes, i.e., dissipation and photon detection. We will discuss and characterize the cavity-QED source together with the detection system shown at the right side of Figs. 1(a) and (b). Let us assume that the quantum efficiency for the detectors is perfect ($\eta = 1$). Two kinds of dissipative processes will be considered: (i) Spontaneous atomic decay from the optical transitions at the common rate $\Gamma$ and (ii) cavity decay of the photons through the mirrors and the irreversible process of their detection. Since $\eta = 1$, the parameters $\kappa_1 \pm = \kappa_2 \pm \equiv \kappa$ will denote the mirror transmission coefficients that, for simplicity, we take the same for all four cavity modes. To account for these dissipative processes one could consider either the Liouville equation for the density operator of the system or the Monte Carlo wave function (MCWF) formalism. In particular, the MCWF formalism is interesting at least for two reasons [20]: (i) in the MCWF treatment of a system belonging to a $N$ dimensional Hilbert space the number of real variables is $2N - 1$ while the density matrix has $N^2 - 1$, and (ii) it provides new insights into the underlying physical mechanisms. In what follows we will use the MCWF formalism. The time evolution of the system, a so-called quantum trajectory, will be calculated by integrating the time-dependent Schrödinger equation with the non-hermitian effective Hamiltonian $H_{\text{eff}}$:

$$H_{\text{eff}} = H_I - \frac{i}{2} \sum_{i=1,2} \sum_{\alpha = +, -} (\Gamma_i^a S_i^a S_i^a + \kappa \alpha_i^a a_i^a),$$

This Hamiltonian includes dissipation due to spontaneous decay of the atom at a rate $\Gamma$ as well as cavity decay at a rate $\kappa$.

For the first scheme, the evolution of the system in the presence of dissipative processes, obtained by averaging over many MCWF simulations, is shown in Fig.4 (a) for the two half-of-a-resonant ROs proposal and in Fig. 4(b) for the STIRAP case. Since, spontaneous atomic decay is the dominant dissipative process in these simulations, the STIRAP process, although slower then the RO process, yields a larger value of the success probability $P$ in generating the state $|E^+\rangle$, defined as $P = |\langle E^+ | \langle \psi(t)_{\text{max}} |^2$. In Fig. 5, we have applied the STIRAP process to the two schemes of Fig. 1 with the best combination of atomic and cavity decay rates of state-of-the-art experiments in the optical domain [21, 22]. For the first scheme we have obtained $P = 0.2$ and for the second one $P = 0.38$.

On the other hand, for the first scheme of Fig. 1, we have evaluated the probabilities for the different photon-emission processes both for the ROs case and for STIRAP case for $\Gamma = 0.08 g$ and $\kappa = 0.053 g$. The result of the statistics is shown in Fig. 6. Column (i) gives the success probability $P$ of producing $|E^+\rangle$ after sending one atom through the setup. For $\Gamma = 0.08 g$ and $\kappa = 0.053 g$, $P = 0.41$ (RO) and $P = 0.2$ (STIRAP). Here $P$ for the STIRAP scheme is lower since the process has to be adiabatic, i.e., significantly slower than the RO process, and it is then more sensitive to cavity decay.

For the second scheme, the probabilities for the different photon-emission events are shown in Figs. 7(a) and 7(c) for $\kappa = 0.1 g$ and $\Gamma = 0.01 g$, and Figs. 7(b) and 7(d) for $\kappa = g$ and $\Gamma = 0.01 g$. Since $|I^0\rangle$ contains no cavity photons, the leakage of two photons through the cavity mirrors indicates the success
Figure 4. Evolution of the system shown in Fig. 1(a) towards the entangled state $|E^+\rangle$ through two truncated ROs (a) and via STIRAP (b). Parameters are: $\Gamma = 0.05g$, $\kappa = 0.005g$ and $\Delta_+ = \Delta_- = 0$. $g$ is the vacuum Rabi frequency at the cavity center that we assume to be the same for both cavities.

Figure 5. Evolution of the system towards the entangled state $|E^+\rangle$ via STIRAP for the scheme that uses a three-level atom (a) with $\Delta_+ = \Delta_- = 0$ and the scheme that uses a diamond atomic configuration (b) with $\Delta_1 = \Delta_2 = 0$. Parameters are: $\Gamma = 0.08g$ and $\kappa = 0.053g$. 
in generating the state $|E^+\rangle$ which, in turns, shows the possibility of operating with high fidelity even in the bad cavity limit, i.e., for $\kappa \approx g$. As it is inferred from Fig. 7(b) and (d), even in the bad cavity limit, the probability of generating an entangled pair of photons (corresponding to column (i)), is larger than the probability of creating a separable state of two photons emitted from the cavity (column (ii)). The later process is due to the photon-cavity decay from state $|B\rangle$, i.e., it originates from diabatic processes. By speeding up the sequence, Figs. 7(c-d), the population of $|B\rangle$ and the probability of generating two non-entangled photons will increase, while the probability of spontaneous emission processes, corresponding to columns (iv) and (v), will reduce. In general, the time duration of the sequence should be optimized to maximize the probability given in column (i) but also the ratio between the probabilities (i) and (ii).

### 6. Entanglement Capability

For both schemes, the results of the source can be improved by post-selection, i.e., by only keeping those events for which one photon from each cavity is registered in the detectors. We thus reduce to the space of two qubits defined by the polarizations of the photons and we can accordingly define the fidelity as $F = \langle E^+ | \rho | E^+ \rangle$, where $\rho$ is the corresponding reduced density matrix. In addition, we use the $S$ parameter of the Clauser-Horne-Shimony-Holt (CHSH) inequality [23] to characterize the entanglement
Figure 8. The CHSH parameter $S$ (Figs. a and b, see text) and the success probability $P$ and fidelity $F$ (Figs. c and d) as a function of the atomic decay for RO (a,c) and the STIRAP process (b,d). The parameters are $\Delta = 0$ and $\kappa = 0.053g$.

7. Practical Imperfections

Next, we will investigate the source feasibility in presence of practical imperfections. Fig. 9 (a,b) shows the success probability $P$ as a function of the deviation from the single and two photon resonance condition for the first scheme of Fig. 1. The figure accounts, e.g., for the presence of a stray magnetic field such that $(\Delta_+ - \Delta_-)/2 \neq 0$, or an electric field yielding $(\Delta_+ + \Delta_-)/2 \neq 0$. For example, for a $J = 0$ to $J = 1$ transition a magnetic field of one Gauss would reduce the fidelity of the cavity-QED source by around 30% for the ROs proposal, while in the STIRAP proposal it would be reduced by only 3%.

On the other hand and concerning to the second scheme, Fig. 9 (c) shows the entanglement capability $S$ as a function of the deviation from the two photon resonance condition and the delay time between the coupling strengths $g_1$ and $g_2$. As soon as the two photon resonance condition is broken the STIRAP procedure fails and the $S$ parameter decreases. On the other hand, the $S$ parameter exhibits a robust behavior against the variation of the delay time between the two interactions as it is seen in the horizontal
axis of Fig. 9 (c).

8. Conclusions

We have proposed a cavity-QED source for the deterministic generation of polarization entangled photon pairs that sharing the same basic elements operates on different physical processes. For the first scheme based on the interaction of a $V$-type level scheme with the two opposite circular polarization modes of two high-Q cavities, we have discussed two possible implementations using either: i) two truncated Rabi oscillations, or ii) an STIRAP process. Although slower than the former implementation, this second one is very efficient and robust under fluctuations of the experimental parameters and, particularly interesting, almost insensitive to atomic decay. The second scheme based on the interaction of a four-level atom in a diamond configuration with the two opposite circular polarization modes of two high-Q cavities, can produce an entangled photon pair even in the bad cavity limit via a STIRAP process. By using the MCWF formalism, we have analyzed and characterized the cavity-QED source in presence of decoherence and experimental imperfections. For state-of-the-art parameters, the RO and the STIRAP proposals of the first scheme have success probabilities of producing a pair of entangled photons of around 40% and 20%, respectively. However, most of the events not leading to an entangled pair of photons can be identified, and for such a post-selection process we have quantified the entanglement capability through the $S$ parameter of the CHSH inequality, which for the same parameters as before is $S = 2.7$ (RO) and $S = 2.3$ (STIRAP). This in both cases clearly exceeds the value $S = \sqrt{2}$ for separable states and the limit $S = 2$ predicted by local hidden variable theories [23]. In the second scheme, fidelities around 80% and $S = 2.32$ are obtained for the bad cavity regime.

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