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Controlled cavity-assisted generation of single and entangled photons in semiconductor quantum dots

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Abstract. We propose a scheme, based on a single semiconductor quantum dot inside a microcavity, for the creation of single and entangled photons with controllable waveform. A lateral electric field allows to charge the quantum dot with a single electron, and breaks the usual optical selection rules. Our scheme utilizes cavity-assisted stimulated Raman adiabatic passage (STIRAP) in order to promote the surplus electron from the ground to the excited state, via excitation of a pump pulse and optical coupling to the charged exciton. This transfer is accompanied by a synchronized emission of a single-photon wavepacket, whose waveform can be controlled by the pump pulse. We investigate the influence of phonon scatterings, and show that they allow to reset the single-photon source. Finally, we propose a slight variant of our scheme which would allow for the creation of entangled multi-photon states. All our simulations are performed with realistic quantum dot and cavity parameters, which allows us to argue that our scheme can be implemented with state-of-the-art quantum dots and microcavities.

1 Introduction

The creation of single photons on demand – first a trigger is pushed and one single photon is emitted after a given time interval – plays an important role in quantum information, e.g., for secure key distributions [1–3] or quantum computation [4]. Gérard and Gayral [5] were the first to propose a turnstile single-photon source based on quantum dots. Their proposal exploits two peculiarities of artificial atoms: first, because of Coulomb renormalizations of the few-particle states, in the decay of a multi-exciton state each photon is emitted at a different frequency; second, because of environment couplings photons are always emitted from the few-particle state of lowest energy. Thus, in the cascade decay of a multi-exciton complex the last photon will always be that of the single-exciton decay, and this photon can be distinguished from the others through spectral filtering, which is usually accomplished by placing the quantum dot in an optical resonator, such as a microcavity [6] or a photonic crystal [7]. Using pulsed laser excitation, single-photon turnstile devices that generate trains of single-photon pulses were demonstrated [6,8–11]. In a somewhat different scheme, electroluminescence from a single quantum dot within the intrinsic region of a p-i-n junction was shown to act as an electrically driven single-photon source [12,13].

A shortcoming of the above scheme is the probabilistic nature of the emission process, which results in a time jitter of the emitted photon [14,15]. In the field of quantum optics with single atoms and ions, it has been demonstrated that single photons with a controlled waveform can be created when the system is coupled with an external laser pulse to a state that strongly interacts with a cavity mode. This scheme is similar to stimulated Raman adiabatic passage (STIRAP) [16,17], where population is channeled by adiabatically transforming the state. In cavity-assisted STIRAP the system is adiabatically promoted from an initial to a final state, and this transfer is accompanied by the synchronized emission of a single-photon wavepacket. Thus, by shaping the exciting laser pulse it becomes possible to directly tailor the waveform of the single photon. Also for quantum dots coherent control [18–21] and STIRAP-related schemes [22–25] have been demonstrated as a versatile means for manipulating quantum dot states.

In this paper we propose a cavity-assisted STIRAP scheme for creating single photons with controlled waveform in semiconductor quantum dots. In order to identify the Λ-type level scheme needed for STIRAP, we consider a quantum dot inside a microcavity which is subject to a lateral electric field [26–28]. This field allows us to charge the quantum dot with a single electron, and breaks the usual optical selection rules such that the electron ground and excited state can both couple to the same charged exciton. It has recently been demonstrated that the lifetime of excited p-type electron states can be of the order of nanoseconds [29], which is sufficient for the implementation of our scheme. Furthermore, phonon relaxation from the excited electron state to the groundstate allows to 'reset' the single-photon source, and enables the production of trains of single photons.

Control over the spin degrees of freedom would also allow for the creation of entangled multi-photon states

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with controlled waveform. Creation of entangled photons based on the multi-exciton cascade decay in semiconductor quantum dots has been proposed in reference [13], and has been demonstrated experimentally in a number of experiments [30–33]. It has been shown that the degree of entanglement critically depends on the finestructure splitting [31,34], as well as on phonon dephasing [35–37] or phonon scatterings [38]. Contrary to this, our cavity-assisted STIRAP scheme is totally immune against environment couplings, and thus might be appealing for applications where a high degree of control is needed.

We have organized our paper as follows. In Section 2 we give a brief introduction into STIRAP and cavity-assisted STIRAP. Although there exists a number of excellent review articles on this topic [16,17,39,40], we have given precedence to a short introduction into the field, mainly in order to establish our notation and to keep the paper self-contained. We also introduce our quantum-dot level scheme and provide details about our simulation approach. Section 3 reports results for the single and entangled photon source. We show that the cavity-assisted STIRAP scheme works for realistic quantum dot and cavity parameters, and we discuss possible shortcomings. Finally, in Section 4 we summarize our proposal.

2 Theory

2.1 STIRAP

Stimulated Raman adiabatic passage (STIRAP) is a technique originally designed for population transfer in atoms or molecules [16,17,40]. It relies on a Λ-type level scheme, such as the one depicted in Figure 1a, where states 1 and 2 are associated with long-lived atomic or molecular states. State 3 is associated with an interconnecting state that is optically coupled to both 1 and 2, which might be short-lived due to radiative losses. Assume that the system is initially in state 1. To bring the system from state 1 to state 2, one uses two laser pulses, where the first one is tuned to the $1 \rightarrow 3$ transition and the second one to the $3 \rightarrow 2$ transition. The two laser pulses are usually denoted as *pump* and *stokes* pulses, and the (time-dependent) Rabi frequencies associated with the optical transitions as Ω_P and Ω_S.

STIRAP provides an optimized pulse sequence that allows to channel the population from state 1 to state 2 in a counter-intuitive order, where the Stokes pulse precedes the pump pulse and both pulses overlap in time. In the ideal case, population can be channeled between states 1 and 2 *without suffering any losses*. To understand why this is the case, we inspect the Hamiltonian that governs the time evolution of the effective three-level system. Within the rotating-wave approximation it reads (we set $\hbar = 1$ throughout) [16,17]

$$H = \frac{1}{2}\begin{pmatrix} 2\Delta_P & 0 & \Omega_P \\ 0 & 2\Delta_S & \Omega_S \\ \Omega_P & \Omega_S & 0 \end{pmatrix}. \qquad (1)$$

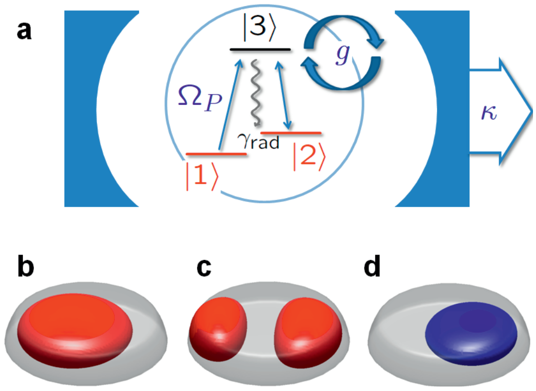

Fig. 1. (Color online) (a) Level scheme of quantum dot inside a microcavity. States 1 and 2 correspond to the (b) ground and (c) excited state of an electron in the quantum dot, which is subject to an in-plane electric field (panel (d) shows the groundstate of the hole). Because of the electric field the usual optical selection rules are broken, and the charged exciton state 3 couples to both 1 and 2. For the explanation of the proposed cavity-assisted STIRAP scheme for creating single and entangled photons see text.

Here Δ_P and Δ_S are the detunings of the central frequencies of the pump and Stokes pulses with respect to the transitions $1 \rightarrow 3$ and $2 \rightarrow 3$, respectively. If the Rabi frequencies Ω_P and Ω_S have a sufficiently slow time variation, the system evolves according to the eigenstates of equation (1), which in case of the two-photon resonance condition $\Delta_P = \Delta_S$ consist of the so-called *trapped state*

$$|a^0\rangle = \cos\theta|1\rangle - \sin\theta|2\rangle \qquad (2)$$

together with two other states that are composed of 1, 2, and 3. The mixing angle θ is defined through $\tan\theta = \Omega_P/\Omega_S$. Importantly, equation (2) even holds when the interconnecting state 3 has a finite lifetime [41]. Population channeling within STIRAP is then achieved by adiabatically transforming state $|a^0\rangle$ from the initial state 1 to the final state 2. To this end, the mixing angle θ is changed in the counter-intuitive pulse sequence from $\theta = 0$ ($\Omega_P = 0$, $\Omega_S > 0$) over $\theta = \pi/4$ ($\Omega_P = \Omega_S$) to $\theta = \pi/2$ ($\Omega_P > 0$, $\Omega_S = 0$). Being an adiabatic scheme, STIRAP is totally robust against small uncertainties or imperfections of the pump and Stokes field, as well as to dephasing or scattering losses of state 3.

2.2 Cavity-assisted STIRAP

A variant of STIRAP is obtained by putting the atom into a cavity, and replacing the action of the Stokes pulse by that of the cavity field [42]. In this scheme the Stokes (cavity) field is always 'on'. Upon arrival of the pump pulse the system's time evolution resembles that of the first part of the STIRAP process, where the mixing angle is changed from $\theta = 0$ ($\Omega_P = 0$, $g > 0$) to $\theta = \pi/4$ ($\Omega_P = 2g$). Here g denotes the coupling constant between atom and cavity. However, as the cavity coupling g cannot be turned off, the system would return back to state 1 when turning off the external pump pulse.

This can be circumvented if the cavity photon can leak out of the cavity, as indicated in Figure 1a by κ. In this case, the cavity field is immediately transformed into a photon field propagating away from the cavity, and the adiabatic population transfer results in the synchronized emission of a single-photon wavepacket [42]. This allows for a deterministic generation of single photons with a waveform solely controlled by the pump pulse, as demonstrated experimentally for atoms and ions trapped inside a cavity [43,44]. Such deterministic single-photon sources might play an important role in quantum networks [3] or quantum computation with linear optics [4].

2.3 Quantum-dot-based single photon source

We now set out to propose a single photon source based on a semiconductor quantum dot inside a microcavity. Quantum dots have been shown to be a viable source for single [5,6,8,9] and entangled photons [13,30–32], and coherent control [18–21] and STIRAP-related schemes [22–25] have been demonstrated as a versatile means for manipulating quantum dot states. In contrast to natural atoms, semiconductor systems allow for the design of monolithic structures and integration in large-scale quantum devices.

In the following we consider a single semiconductor quantum dot inside a microcavity. We assume that the quantum dot is placed inside a field-effect structure, where the electric field is applied in the *lateral* direction [26–28], i.e., perpendicular to the growth direction. The lateral electric field has the following effects: first, it allows to charge the quantum dot with a single electron [27]; second, it allows to fine tune the quantum dot transitions with respect to the cavity [45], and to bring quantum dot and cavity into resonance; finally, it breaks the optical selection rules [26,28].

Panels (b)–(d) of Figure 1 schematically show the quantum dot states underlying our proposal. The ground and excited state of the single-charged quantum dot are depicted in panels (b) and (c). Because of the electric field, the electron wavefunction is shifted to the left. In contrast, the hole wavefunction, Figure 1d, is shifted to the right. We next assign the quantum dot states to the Λ-type level scheme as follows: states 1 and 2 are associated with the ground and excited state of the single-electron-charged quantum dot. The interconnecting state 3 is associated with the charged exciton state X^-, approximately consisting of the electron and hole wavefunctions depicted in panels (b)–(d). It is important to realize that the optical coupling between states 1 and 2 is only possible because of the field-induced breaking of the optical selection rules. As demonstrated in references [26,28] in great detail, the electric field provides a highly flexible means to tailor the transition energies and optical matrix elements at will. In this respect, the setup under study appears to advantageous in comparison to other Λ-type schemes in quantum dots which are controlled by external magnetic fields [46].

A few comments are in place. First, contrary to atomic systems state 2 has a finite lifetime, as it can decay back to state 1 via phonon emission. Lifetimes of the order of nanoseconds have been demonstrated [29], which is sufficient for our proposal (see discussion below). However, phonon scatterings might be also beneficial as they allow to reset the single photon source, and thus to generate repeatedly single photons with a GHz repetition rate. Second, in our considerations so far we have neglected the spin degrees of freedom. In case that the cavity sustains two degenerate modes with opposite polarizations, the cavity-assisted STIRAP scheme for the single-photon generation could be driven with an unpolarized (or cross-polarized) pump pulse for both polarization transitions in parallel. In case that the cavity sustains only one mode, or if single photons with a well-defined polarization are needed, the electron spin has to be aligned prior to the cavity-assisted STIRAP scheme, which could be achieved through magnetic fields or optical pumping [47]. Control over the spin degrees of freedom would additionally open a potentially powerful route for the generation of highly entangled photon states, as will be discussed at the end of this paper.

2.4 Simulation approach

We now have all ingredients at hand to theoretically analyze the production of a single photon wavepacket from a quantum dot inside a microcavity. Our basis for the quantum dot and cavity states then consists of four states: in the initial one $|1;0_{\rm cav}\rangle$ the electron is in state 1 (panel (b) of Fig. 1) and the cavity is empty; the pump pulse promotes the system into the charged exciton state $|3;0_{\rm cav}\rangle$; this state is coupled (by the cavity coupling constant g) to the state $|2;1_{\rm cav}\rangle$, where the electron is in the excited state 2 (panel (c) of Fig. 1) and one cavity photon is present; finally, the cavity photon can leak out of the cavity, and the system is promoted to the terminal state $|2;0_{\rm cav}\rangle$ of the cavity-assisted STIRAP process. Quite generally, in case that phonon scatterings can bring back the system from 2 to 1, also states with more than a single photon in the cavity might become populated. However, due to the strong losses of the cavity these states are of only minor importance.

We describe the system's dynamics in presence of the pump pulse through a master equation of Lindblad form [48]

$$\dot{\rho} = -i[H,\rho] - \frac{1}{2}\sum_k \left(L_k^\dagger L_k \rho + \rho L_k^\dagger L_k - 2 L_k \rho L_k^\dagger \right), \quad (3)$$

where H is the Hamiltonian accounting for the coherent time evolution, and the Lindblad operators L_k account for scatterings and dephasing. H includes the detuning Δ_P between the central pump frequency and the $1 \to 3$ transition, the detuning $\Delta_{\rm cav}$ between the cavity photon and the $2 \to 3$ transition, the pump pulse coupling Ω_P between states 1 and 3, and the cavity coupling g between states $|3;0_{\rm cav}\rangle$ and $|2;1_{\rm cav}\rangle$. The Lindblad operators accounting

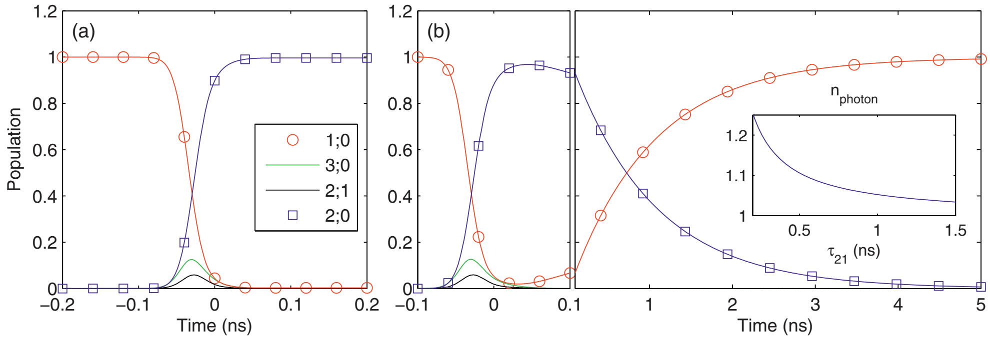

Fig. 2. (Color online) Simulations of single photon generation through a cavity-assisted STIRAP process. We use the parameters listed in Table 2 and assume a two-photon resonance with $\Delta_P = \Delta_{\text{cav}} = 0.1$ meV. (a) Population transients for the states composed of the quantum dot states 1, 2, 3 (see Fig. 1a) and the cavity photon. For the Gaussian pump pulse the initial state $|1;0_{\text{cav}}\rangle$ is directly channeled to the final state $|2;0_{\text{cav}}\rangle$ upon emission of a coherent photon wavepacket. (b) Single-photon generation in presence of phonon scatterings between states 2 and 1, with $\tau_{21} = 1$ ns. In the inset we show the mean number of emitted photons as a function of τ_{21}.

Table 1. Scattering channels considered in this work. The Lindblad operators $L_k = \sqrt{\gamma_k}\,\mathcal{T}_k$ associated with these scatterings are given by the transition operators $\mathcal{T}_k$, multiplied with the square root of the corresponding scattering rate γ_k. The QD relaxation rate γ_{21} accounts for phonon scatterings.

Scattering channel	Scattering rate	Transition operator
Cavity decay	κ	$\lvert 3;0_{\text{cav}}\rangle\langle 3;1_{\text{cav}}\rvert$
QD dephasing	γ_d	$\lvert 3;0_{\text{cav}}\rangle\langle 3;0_{\text{cav}}\rvert$
QD radiative decay	γ_{rad}	$\lvert 1;0_{\text{cav}}\rangle\langle 3;0_{\text{cav}}\rvert$
	γ_{rad}	$\lvert 2;0_{\text{cav}}\rangle\langle 3;0_{\text{cav}}\rvert$
QD relaxation	γ_{21}	$\lvert 1;0_{\text{cav}}\rangle\langle 2;0_{\text{cav}}\rvert$
	γ_{21}	$\lvert 1;1_{\text{cav}}\rangle\langle 2;1_{\text{cav}}\rvert$

Table 2. Parameters used in our simulations. The quality factor Q is related to the cavity loss rate via $\kappa = \omega_{\text{cav}}/Q$, where $\omega_{\text{cav}} = 1.3$ eV is the cavity photon energy. For the pump pulse we assume a Gaussian with a maximum of Ω_P and a full width at half maximum (FWHM) of τ_P.

Parameter	Symbol	Value
Cavity: quality factor	Q	5000
Cavity: coupling strength	g	0.1 meV
Pump pulse: max. Rabi energy	Ω_P	0.2 meV
Pump pulse: FWHM	τ_P	80 ps
QD: radiative decay time	τ_{rad}	5 ns
QD: dephasing time	τ_d	20 ps

for cavity decay as well as relaxation and dephasing in the quantum dot are listed in Table 1.

3 Results

3.1 Single-photon generation

In our simulations we assume a pump pulse with a Gaussian envelope, and solve the master equation of equation (3) numerically through direct integration. For the cavity we assume a central frequency of 1.3 eV and a moderate quality factor of $Q = 5000$, corresponding to a cavity photon lifetime of about 2.5 ps. The cavity coupling constant $g = 0.1$ meV corresponds to a typical value of cavity-QED experiments with semiconductor quantum dots [49,50]. For best performance of STIRAP, the maximum of the Rabi energy should be comparable to g. All parameters of our simulations, including the scattering and dephasing losses of the inter-connecting state 3, are listed in Table 2.

Figure 2a shows results of our simulations for a two-photon resonance with $\Delta_P = \Delta_{\text{cav}} = 0.1$ meV and for an artificial neglect of phonon scatterings between states 1 and 2. We observe a clear STIRAP-type transition between states 1 and 2 where the system's wavefunction is adiabatically transformed by the pump pulse. This transition is accompanied by the emission of a single-photon wavepacket (not shown), with an envelope precisely following the pump pulse $\Omega_P(t)$ (because cavity losses are much faster than the population channeling induced by the pump pulse [51][1]). Thus, by tuning the shape of the pump pules one can directly control the waveform of the emitted photon.

From our simulations we found that the temporal width of the pump pulse should stay above say 80 ps in order to significantly suppress the population of the inter-connecting state 3. Because of this suppressed population, the losses in state 3 have no decisive influence on our simulation results; stronger dephasing losses or an increased radiative decay rate τ_{rad}^{-1} would therefore not alter the population transients. We also found that for smaller Q values the fidelity of the population transfer decreases. While for $Q = 5000$ the probability of finding the system finally in the 2 state is above 99%, the probability drops to 94% for $Q = 2000$. This is due to the broadening of the

[1] This finding is different to the study of atoms falling through a high-quality cavity, where also the coupling changes with time, as discussed in [51]. There the authors found a single-photon wavefourm that is *independent* of the pump pulse shape.

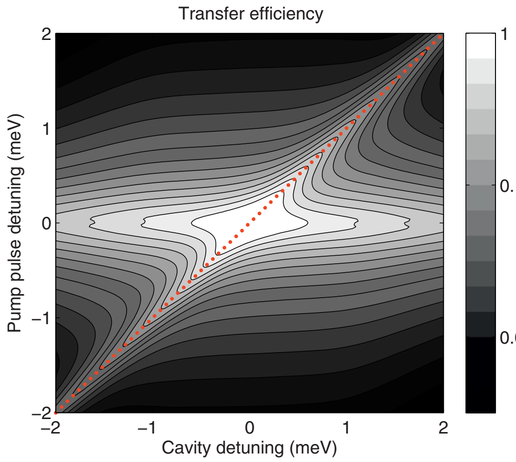

Fig. 3. (Color online) Transfer efficiency of cavity-assisted STIRAP sequence for different detunings, and in absence of phonon scatterings. The dotted line indicates detunings with two-photon resonances. The transfer works efficiently over a broad range of Δ_P and $\Delta_{\rm cav}$.

interconnecting state, as consequence of the high leakage rate κ, and the resulting inhibition of adiabatic transfer.

When phonon scatterings are considered, Figure 2b, the system is reset to the initial state after the emission of the photon. Depending on the phonon rate τ_{21}^{-1}, this reset process takes a few nanoseconds [29]. On the other hand, due to this scattering channel there is a small probability that the system returns to state 1 while the pump pulse is still on, in which case a second photon can be emitted. In the inset of Figure 2b we report the mean number of emitted photons $n_{\rm photon}$ as a function of the phonon scattering time. We find that for values of τ_{21} around 1 ns the emission probability for a second photon is around 5%, which we consider to be reasonably low, in particular in view of the not perfect collection efficiencies of present-day microcavities. We have not attempted to optimize the pump pulse duration and strength in presence of phonon scatterings. When additional electron states are considered, such as another almost degenerate p-type state, population can become shelved there. Further simulations (not shown) revealed that such shelving does not noticeably affect our results, as long as the phonon decay time to the initial state 1 is comparable to τ_{21}.

In Figure 3 we show the transfer efficiency for different pump and cavity detunings, in absence of phonon scatterings. The dotted line corresponds to situations where the two-photon resonance condition holds. One observes that the transfer process works perfectly well within a broad range of detunings. For this reason, it is not necessary to perfectly align state 3 with the cavity. Also the details of the pump pulse regarding possible imperfections or noise are not overly critical within our scheme.

3.2 Entangled-photon generation

Finally, we consider an extension of our cavity-assisted STIRAP scheme, which relies on the possibility to initialize and manipulate the spin of the charging electron [52]. Spin preparation and manipulation have been demonstrated experimentally [47,53,54]. Due to the spin degrees of the electron, the level scheme depicted in Figure 1a in principle consists of *two equivalent* level schemes: in the first one the surplus electron has spin up, and in the second one spin down orientation. Controlling the polarization of the pump pulse Ω_P allows to address the two sets of spin states selectively.

If the system is initially in the $|1\uparrow\rangle$ state, where the arrow denotes the electron spin orientation, the pump pulse will create a photon with say horizontal polarization H. Conversely, the initial $|1\downarrow\rangle$ state will result in the emission of a photon with vertical polarization V. When the system is initially prepared in a superposition state $\Psi \propto |1\uparrow\rangle + |1\downarrow\rangle$, the application of the pump pulse results in a state

$$\Psi \propto |2\uparrow;\mathsf{H}\rangle + |2\downarrow;\mathsf{V}\rangle \to |1\uparrow;\mathsf{H}\rangle + |1\downarrow;\mathsf{V}\rangle \tag{4}$$

where the electron spin and the emitted photon are entangled. On the right-hand side of equation (4) we have indicated that at the end of the pump pulse the system is reset to the initial state via phonon emission. Thus, when after the reset a second pump pulse arrives, the system is brought to

$$\Psi \propto |2\uparrow;\mathsf{HH}\rangle + |2\downarrow;\mathsf{VV}\rangle \to |1\uparrow;\mathsf{HH}\rangle + |1\downarrow;\mathsf{VV}\rangle, \tag{5}$$

where the electron spin is now entangled with the two consecutively emitted photons. It is obvious that the above scheme can be extended to even more photons. Finally, to disentangle the photons from the electron spin, it would be necessary to perform a projective measurement in a crossed electron-spin basis, or to coherently manipulate the electron spin and to perform a projective measurement of the most recently emitted photon [52]. The details of such schemes certainly provide an experimental challenge, but we believe that this points into a promising direction where control over the spin and charge degrees of freedom opens the possibility to not just generate Bell-type states, but a much broader class of highly entangled photon states.

4 Summary

To summarize, we have presented a cavity-assisted STIRAP scheme suitable for the controlled generation of single photons. The proposed system consists of a single semiconductor quantum dot inside a microcavity. By applying a lateral electric field, the quantum dot can be charged with a single electron and the usual optical selection rules are broken. As consequence, optical transitions between the ground and excited electron states, and the charged exciton are possible. In the resulting Λ-type level scheme the optical transition between the charged exciton and the excited electron state are assumed to be in resonance with the cavity mode. Thus, when the system is initially in the electron groundstate and is driven by an external pump pulse, whose central frequency is tuned to the transition between the groundstate and the charged exciton, an adiabatic transfer to the excited electron state occurs which is accompanied by the emission of a photon wavepacket whose envelope is controlled by the pump pulse. Because of phonon scatterings, after a time of the order of nanoseconds the system is reset to the groundstate. This allows for the repeated generation of single photons with a GHz repetition rate. We have also presented a variant of this scheme, where control over the electron spin degrees of freedom allows for the generation of entangled photons. The requirements for our scheme are compatible with presentday quantum dot and microcavity systems, and the scheme also works in presence of imperfections of the driving pump pulse and of dephasing or scattering losses of the charged-exciton state.

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