Entangled Photon Pairs Produced by a Quantum Dot Strongly Coupled to a Microcavity

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We show theoretically that entangled photon pairs can be produced on demand through the biexciton decay of a quantum dot strongly coupled to the modes of a photonic crystal. The strong coupling allows us to tune the energy of the mixed exciton-photon (polariton) eigenmodes and to overcome the natural splitting existing between the exciton states coupled with different linear polarizations of light. Polariton states are moreover well protected against dephasing due to their lifetime of ten to a hundred times shorter than that of a bare exciton. Our analysis shows that the scheme proposed is achievable with the present technology.

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Since the first treatment by Einstein, Podolsky, and Rosen (EPR) [1], quantum entanglement (EPR correlation) has been a widely discussed topic in physics [2]. The development of quantum information and communication [3] opened fascinating applications for EPR correlations, e.g., a secret key exchange via the Bennet-Brassard protocol [3,4]. A large number of proposals and experimental works on entangled photon sources based on these predictions have been published recently [5–11]. In this framework, semiconductor quantum dots (QDs) appear to be good candidates to implement a solid state source of entangled photon pairs on demand, because of the long decoherence time of their carriers. The basic idea which has attracted the strongest attention is to use the photon pairs produced by the decay of a biexciton (bX) [12]. The two possible decay paths for the bX in the ideal case can be distinguished only by measuring the polarization of the two emitted photons of each cascade [Fig. 1(a)]. This system therefore appears to be a perfect solid state source of EPR pairs. However, even though QDs are often thought of as artificial atoms, they deviate from the ideal scheme because of the coupling between the exciton states with total angular momentum $+1$ and -1. The anisotropic electron-hole interaction [13,14] splits the exciton states into two modes linearly polarized along the crystallographic axis of the crystal H and V. As a result, the photons emitted in the bX decay in a real QD are not polarization-entangled, because they can be distinguished through their energy. Various solutions which allow us to overcome this splitting have been proposed: carefully selected QDs [15,16], filtering of the emission lines by the optical mode of a planar cavity [5], or application of an electric field [17–19]. Recently, two works have reported photon correlation measurements violating the Bell inequalities. One is based on the application of a magnetic field to control the position of the eigenstates [6]. The other [8] is based on the monochromatic detection of the photons emitted by the small overlap region between the split exciton lines.

Another timely topic in modern physics is the strong coupling regime (SCR) in semiconductor microcavities. The SCR has been first achieved in planar cavities [20], where it allowed engineering of the dispersion and of the physical properties of the mixed eigenmodes of the cavity [21]. Recently, the SCR between an electronic excitation of a single QD and the optical mode of a photonic crystal has been reported by four different groups [22–26]. These implementations are opening a new research field where the precise control of the energy levels and the nature of the eigenmodes of the systems is possible.

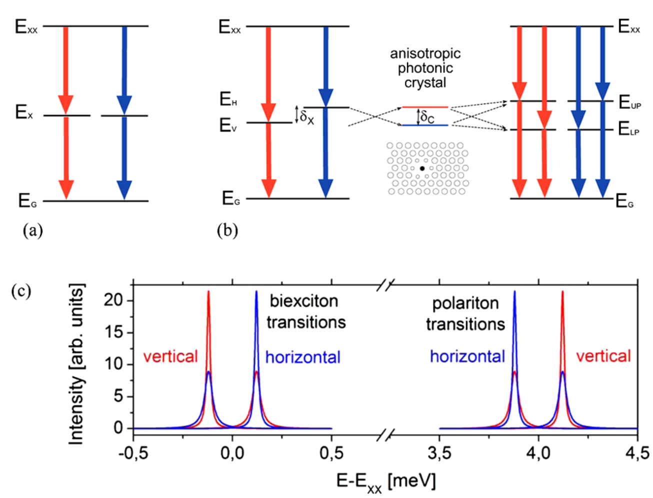

FIG. 1 (color online). (a) Schematic illustration of the ideal bX radiative cascade with $\delta_X = 0$. (b) The left figure shows the transitions in QDs with two split exciton levels E_V and E_H. The middle part shows the eigenstates of the anisotropic photonic crystal and the scheme of the photonic crystal (open circles) as proposed in Ref. [28] with the embedded QD (black point). The sketch on the right shows the bX decay in the SCR. (c) shows the calculated PL spectra of the bX and polariton transitions. The different polarizations are indicated with red/light gray (V) and blue/dark gray (H).

In this Letter, we propose to use these new possibilities in order to achieve energy degenerate exciton-photon (polariton) modes and thus to recover the ideal bX decay picture giving rise to polarization-entangled photon pairs.

A scheme depicting our proposal is sketched in Fig. 1(b). The left part illustrates the bX decay in a realistic semiconductor QD. Starting from the bX state with the energy E_{XX}, the cascade passes through two intermediate exciton states indicated with E_H for horizontal and E_V for vertical polarization, to reach the ground state. The two bare exciton levels are split by an energy $\delta_X = E_H - E_V$ due to the exchange interaction, and the decay path can be distinguished by the photon energy.

In order to make the intermediate states degenerate, we propose to embed the QD within an anisotropic photonic crystal. Its cavity modes polarized H and V are split by an energy $\delta_C = E_C^H - E_C^V$, where ($E_C^{H,V}$) denotes the cavity mode energy for each polarization H and V. Within the SCR, an exciton and a photon of a given polarization couple and give rise to two similarly polarized polariton states. The energies of the four polariton states read:

$$E_{\pm}^{H,V} = \frac{E_{H,V} + E_C^{H,V}}{2} \pm \frac{1}{2}\sqrt{(E_{H,V} - E_C^{H,V})^2 + 4\hbar^2\Omega_R^2}, \quad (1)$$

Ω_R is the half of the Rabi splitting, which is taken equal for both polarizations [27]. The + sign stands for the upper polariton (UP) states and the − sign for the lower polariton (LP) states. The pairs of polariton states are degenerate ($E_{\pm}^H = E_{\pm}^V$) if $E_C^H = E_V$ and $E_C^V = E_H$, which means that each resonance for V- and H-polarized light is adjusted to the energy of the exciton state coupled to the perpendicular polarization. In the same time, the bX transition is not strongly interacting with the cavity modes, because the binding energy of the bX is at least 1 order of magnitude larger than $\hbar\Omega_R$. This resonance can interact with another photonic mode, but we do not want to address this case here, and we assume that the bX emission energy is not perturbed by the presence of the cavity. The right-hand side of Fig. 1(b) shows the resulting distribution of the energy levels. There are four possible decay channels for the bX. The two decay paths using the UP as an intermediate state produce polarization-entangled photon pairs, which is also the case for the decay paths using the LP. This configuration is particularly original and probably useful, since it allows us to produce two independent EPR pairs. The corresponding photoluminescence (PL) spectra are shown in Fig. 1(c). The spectrum for each polarization consists of two groups of two peaks. The group with the lower energy corresponds to the bX decay to the polariton states. The group with the higher energy corresponds to the decay of the polariton states toward the ground state. The technological requirements for this scheme are, however, quite strong. The first condition is that $2\hbar\Omega_R > \delta_X$. The second condition is that the splitting between the optical modes is equal to the splitting between the QD modes with an opposite sign $\delta_X = -\delta_C$. The first condition is usually well fulfilled. In InAs-based structures, δ_X is of the order of 0.05–0.1 meV, whereas $2\Omega_R \approx 0.15$–0.25 meV. The second condition, because it is an equality, and because of the small value of δ_X, seems quite demanding and would, in practice, require the growth and study of many structures.

We therefore propose another configuration, conceptually less ideal, but which allows an easier experimental implementation. We propose to use a structure showing a splitting δ_C larger than δ_X. Neither the exact value nor even the sign of δ_C play a crucial role in this scheme. In Ref. [28], for instance, the splitting measured is about 0.5 meV for a cavity with quality factor $Q > 10\,000$, and in Ref. [29] it is shown how the X- and Y-polarized modes of a cavity can be tuned independently. Figure 2(a) shows the eigenenergies versus the exciton-photon detuning $\delta_{C-X} = \frac{E_C^H + E_C^V}{2} - \frac{E^H + E^V}{2}$, keeping δ_X and δ_C constant. This tuning of the exciton energy can be performed experimentally, for example, by changing the temperature of the sample [25,26]. We consider here the case where δ_X and δ_P have the same sign. For a wide range of detunings, the H-polarized LP and the V-polarized UP are almost degenerate. The decay channels of the bX are shown in Fig. 2(b). The PL spectra in two polarizations for positive detuning

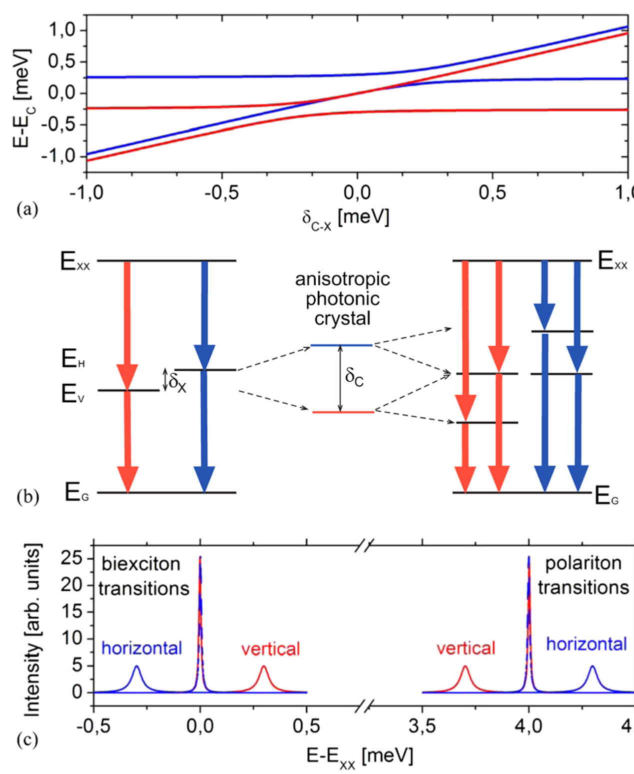

FIG. 2 (color online). (a) Calculated energies of the polariton states for different detunings δ_{C-X} with $E_C = (E_C^H + E_C^V)/2$, $\delta_X = 0.1$ meV, $\delta_C = -0.5$ meV, and $2\hbar\Omega_R = 0.22$ meV. Different polarizations are indicated with red/light gray (V) and blue/dark gray (H). (b) Distribution of the energy levels for $\delta_{C-X} = 0$. (c) PL spectra for both polarizations.

are shown in Fig. 2(c). For each polarization, the peaks with the higher energy and the lower energy belong to the same decay cascade. The two central peaks belong to the same decay cascade as well. The decay channel involving the H-polarized UP and the decay channel involving the V-polarized LP cannot be distinguished by energy measurements but only by their polarization. As noted before, this degeneracy can also be found if δ_X and δ_C have opposite signs. Figure 3(a) shows the eigenenergies versus δ_{C-X} in that case. The energy degeneracy now occurs at negative detuning between the LP states (H and V) and at positive detuning between the UP states (H and V). The decay channels of the bX for the negative detuning case are shown in Fig. 3(b). The PL spectra for negative detunings are shown in Fig. 3(c). Note the difference in the degeneracy of the peaks in Figs. 2(c) and 3(c): In the first case LP is degenerate with UP of different polarization, and in the second case LP is degenerate with LP. A quality of the scheme that we propose is the high degree of entanglement which can be expected. The general form of the wave function of two photons generated by the bX decay can be written as [8]:

$$|\Psi\rangle = (\alpha_{\rm LP}|p_H^{\rm LP}\rangle + \alpha_{\rm UP}|p_H^{\rm UP}\rangle)|HH\rangle + (\beta_{\rm LP}|p_V^{\rm LP}\rangle + \beta_{\rm UP}|p_V^{\rm UP}\rangle)|VV\rangle, \quad (2)$$

where $\alpha_{\rm LP}$, $\alpha_{\rm UP}$, $\beta_{\rm LP}$, and $\beta_{\rm UP}$ are the weights of the possible transitions satisfying

$$|\alpha_{\rm LP}|^2 + |\alpha_{\rm UP}|^2 + |\beta_{\rm LP}|^2 + |\beta_{\rm UP}|^2 = 1. \quad (3)$$

The ket $|p_{H(V)}^{\rm LP(UP)}\rangle$ is the coordinate part of the two-photon wave packet for each polarization H and V, the kets $|HH\rangle$ and $|VV\rangle$ are the polarization part of the wave function corresponding to the H- and V-polarized photons, respectively. The radiative decay of polariton states is governed by the cavity photon lifetime τ_C, which is typically of the order of 10–20 ps—much faster than the exciton radiative decay. In the same time the transitions from one intermediate polariton state to another and the dephasing of these states have similar rates as in the bare exciton case, and the decay of the coherent intermediate state, which can play some important role in bare QDs systems [30], can be safely neglected here.

For the ideal case presented in Fig. 1(b), the density matrix of the system can be written as

$$\rho = \begin{pmatrix} |\alpha_{\rm LP}|^2 + |\alpha_{\rm UP}|^2 & 0 & 0 & \gamma \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \gamma^* & 0 & 0 & |\beta_{\rm LP}|^2 + |\beta_{\rm UP}|^2 \end{pmatrix}, \quad (4)$$

where

$$\gamma = \alpha_{\rm LP}\beta_{\rm LP}^*\langle p_H^{\rm LP}|p_V^{\rm LP}\rangle + \alpha_{\rm UP}\beta_{\rm UP}^*\langle p_H^{\rm UP}|p_V^{\rm UP}\rangle, \quad (5)$$

where $\langle p_H^{\rm UP}|p_V^{\rm LP}\rangle = 0$ and $\langle p_H^{\rm LP}|p_V^{\rm UP}\rangle = 0$ because they correspond to overlap between the wave functions of two photons of different energies. One can estimate the degree of entanglement by using the Peres criterion [31], which gives that the entanglement exists if and only if $|\gamma| > 0$. Two photons reach their maximally EPR correlated state for $|\gamma| = 1/2$ [28]. The polarization-entangled photon pairs can be grouped by energy, one pair with $E_{\rm LP}$ and one with $E_{\rm UP}$. It is possible to define spectral windows of a detector to count only the entangled photons using one of the polariton levels, which is expressed as a projection of the wave packet. The wave function $|\Psi\rangle$ has to be recast as $P|\Psi\rangle/|P|\Psi\rangle|^2$. Fixing the spectral windows to the energy of the lower polariton branch $E_{\rm LP}$ and $E_{XX} - E_{\rm LP}$ leads to the disappearance of the upper branch terms. The diagonal terms of the density matrix (4) reduce to $|\alpha_{\rm LP}|^2$ and $|\beta_{\rm LP}|^2$. The off-diagonal components of the density matrix read

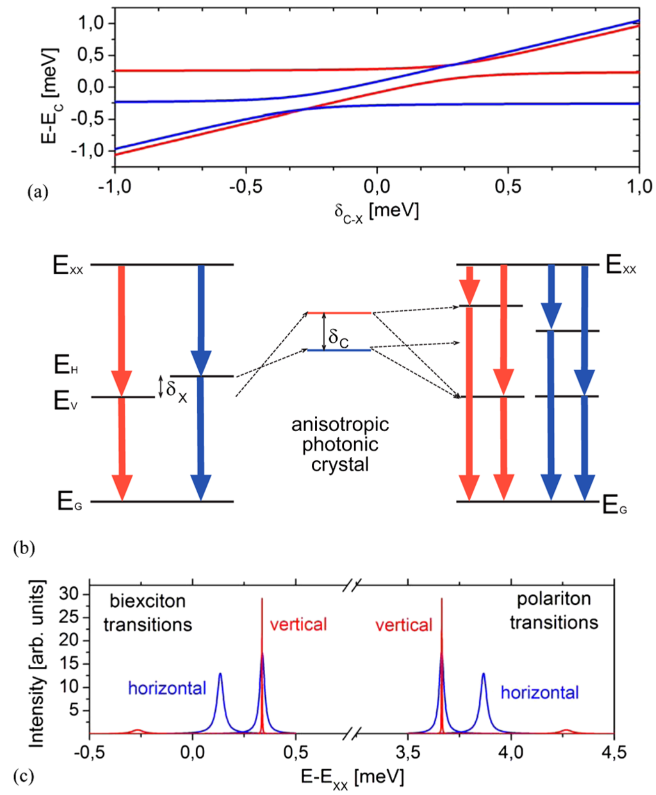

FIG. 3 (color online). (a) Calculated energies of the polariton states for different detunings δ_{C-X} with $E_C = (E_C^H + E_C^V)/2$, $\delta_X = -0.1$ meV, $\delta_C = 0.5$ meV, and $2\hbar\Omega_R = 0.22$ meV. Different polarizations are indicated with red/light gray (V) and blue/dark gray (H). (b) Distribution of the energy levels for a positive δ_C and a negative δ_X. (c) PL spectra for both polarizations and a detuning $\delta_{C-X} = -0.275$ meV.

$$\gamma' = \frac{\alpha_{\rm LP}\beta_{\rm LP}^*\langle p_H^{\rm LP}|P|p_V^{\rm LP}\rangle}{|\alpha_{\rm LP}|^2|\langle p_H^{\rm LP}|P|p_H^{\rm LP}\rangle| + |\beta_{\rm LP}|^2|\langle p_V^{\rm LP}|P|p_V^{\rm LP}\rangle|}. \quad (6)$$

γ' is equal to $1/2$ if $\alpha_{\rm LP} = \beta_{\rm LP}$, which means that the two decay channels for the bX have the same amplitude, and the photon packets for different polarizations overlap perfectly. The two-photon function $|p_{H(V)}^{\rm LP}\rangle$ is determined within the dipole and rotating wave approximation and by using the perturbation theory [8,32] as:

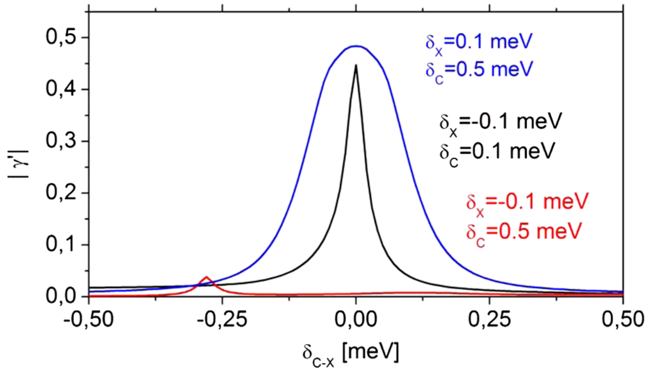

FIG. 4 (color online). Calculated $|\gamma'|$ versus δ_{C-X}. Each color corresponds to a scheme from a different figure: 1 (black), 2 (blue/dark gray), and 3 (red/light gray). Two detectors are placed at the energies $E_{XX} - E_{\rm LP}$ and $E_{\rm LP}$, with $W = 0.2$ meV.

$$A_H^{\rm LP} \equiv \alpha_{\rm LP}\langle k_1, k_2 | p_H^{\rm LP}\rangle = \frac{x_{\rm ex}^{H,\rm LP}\sqrt{\Gamma_{XX}}x_{\rm ph}^{H,\rm LP}\sqrt{\Gamma_{\rm LP}^H/2\pi}}{(|k_1| + |k_2| - \varepsilon_{XX}^H)(|k_2| - \varepsilon_{\rm LP}^H)}, \tag{7}$$

where k_1 and k_2 are the momenta of the photons ($\hbar$, $c = 1$), $\varepsilon_{XX}^H = E_{XX} - i\Gamma_{XX}$, and $\varepsilon_{\rm LP}^H = E_{\rm LP} - i\Gamma_{\rm LP}^H$. A similar expression can be obtained for $A_V^{\rm LP}$. The radiative width $\Gamma_{\rm LP}^H = |x_{\rm ph}^{H,\rm LP}|^2/\tau_C$, where $x_{\rm ph\ (ex)}^{H,\rm LP}$ are the photon (exciton) Hopfield coefficients of the polariton state. On the other hand, the radiative width of the bX-polariton transition is proportional to the exciton fraction of the polariton. Equation (7) has a clear physical meaning: The wave function of a pair of emitted photons in the reciprocal space is a Lorentzian packet, whose width is given by the broadenings of the exciton and bX levels.

Figure 4 shows the dependence of $|\gamma'|$ versus δ_{C-X}, computed by using

$$\gamma' = \frac{\iint dk_1 dk_2 A_H^{\rm LP*} W A_V^{\rm LP(UP)}}{\iint dk_1 dk_2 A_H^{\rm LP*} W A_H^{\rm LP} + \iint dk_1 dk_2 A_V^{{\rm LP}(UP)*} W A_V^{\rm LP(UP)}}, \tag{8}$$

where W represents the two spectral windows, and the upper branch transition amplitudes have been used to calculate $|\gamma'|$ in scheme 2. The maximum value of $|\gamma'|$ for scheme 3 is not optimal, due to the difference between the exciton and photon fractions of the degenerate polariton states. The asymmetry of the curves comes from the small lifetimes for negative detuning δ_{C-X}. Consequently, the linewidth is larger than the energy difference between the two polariton states, which yields $\langle p_H^{\rm LP}|P|p_V^{\rm LP}\rangle > 0$. On the other hand, the degree of entanglement achieved within the schemes proposed in Figs. 1 and 2 reaches almost the maximum value 1/2, which makes these configurations quite favorable.

In conclusion, the SCR between light and matter allows engineering of the optical properties of quantum structures. We have shown that this approach allows transforming the split QD exciton levels into degenerate polariton levels. This scheme has moreover the advantage of rapidly decaying intermediate states, which are therefore well protected from dephasing. We believe that our proposal can be realistically achieved experimentally by using QDs embedded in photonic crystals, which is promising to implement a solid state source of EPR photon pairs for applications in quantum computing and quantum information processing.

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