Reversing the temporal envelope of an heralded single photon using a cavity

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We demonstrate a way to prepare single photons with a temporal envelope that resembles the time reversal of photons from the spontaneous decay process. We use the photon pairs generated from a time-ordered atomic cascade decay~~as a starting point:~~ : the detection of the first photon of the cascade is used as a herald for the ground-state transition resonant second photon. We show how coupling the heralding photon into an asymmetric Fabry-Perot cavity ~~seemingly~~ reverses the temporal shape of the ~~heralded~~ twin photon from a decaying to a rising exponential envelope. A single photon with such an exponentially rising temporal envelope ~~would~~ is expected to be ideal for interacting with two level systems. ~~Using the analogy between an atom and a cavity we demonstrate a~~ As a proof-of-principle, we use the a longitudinal mode of an optical cavity as a model for a two level atom and we present an experiment on how ~~these photons can be used for strong interaction with a single atom.~~ the temporal profile of the single photons affects the strength of interaction with it.

Absorption of a single photons by a single atom or an ensemble of atoms is an interesting problem from the fundamental point of view, and is also essential for many quantum information protocols [1–3]. One of the requirements for an efficient absorption is that the temporal shape of the incident photon ~~should be~~ is the time reversal of the photon from the spontaneous decay process [4, 5]. Temporally shaped light pulses have been utilized in many recent experiments to achieve efficient interactions between light and matter [6, 7]. In particular, the advantage of using a rising exponential shaped single photons for absorption in an atomic ensemble was demonstrated in [8], and shaped multiphoton pulses for exciting a single atom was demonstrated in [9].

Efficient preparation of single photons with narrow bandwidth and a rising exponential envelope is not trivial. One solution is the direct modulation of an heralded photon generated by an atomic medium [10]. This ~~techniques result~~ technique results in unavoidable losses because of its inherently filtering nature. We have previously demonstrated a scheme to generate rising exponential shaped single photons with usable rate by heralding on the photon pairs produced by cascade decay [11]. The drawback of ~~such~~ this scheme is that the photon presenting the rising exponential envelope is not resonant with ~~a transition from the ground state .~~ any atomic ground state transition. In this letter, we ~~adapt~~ combine the asymmetric cavity design used by Bader et al. [12] with the well known temporal correlation properties of photon pairs [13] to invert the temporal envelope of the generated photon pairs: with the proper heralding sequence we obtain a rising exponential single photon resonant with ~~the atoms in the ground state .~~

a ground state transition of ^{87}Rb.

The photons ~~pairs~~ produced by atomic cascade decay have a well defined time order. The first photon of the cascade (signal) is generated before the photon resonant with the ground state (idler). ~~Such a pair may~~ The resulting state can be described by a two photon wave function [14] of the form

$$\psi(t_s, t_i) = A\, e^{-(t_i - t_s)/2\tau}\,\Theta(t_i - t_s)\,, \tag{1}$$

where t_s, t_i are the detection times of the signal and the idler photons and Θ is the ~~heaviside~~ Heaviside step function. In this notation, and the probability of observing a pair is proportional to $|\psi(t_s, t_i)|^2$. The exponential envelope and the decay time τ is inherited from the atomic evolution in the intermediate level of the cascade decay. If the detection of a signal photon is used as herald, the idler mode has a single photon state with a exponentially decaying temporal envelope starting at $t_i = t_s$. Similarly, if the detection of a idler photon acts as a herald, the ~~resuling~~ resulting idler photon envelope has an exponentially rising temporal envelope.

~~The conversion of~~

An asymmetric cavity with the appropriate parameters can transform a light field with an exponentially rising envelope into one with a decaying envelope~~by the asymmetric cavity [12] can now be used to modify the idler mode , and for appropriate parameters, will reverse the time order of the detection of the photonpair~~ [12] . Coupling the signal mode into an properly tuned asymmetric cavity before heralding results in a "time reversed" time envelope for the idler photon.

~~In order to explain this, we refer to the experimental arrangement~~ The experimental setup is shown in Fig. 1. The asymmetric cavity is formed by a partially reflective mirror M1, and a highly reflective mirror M2. The effect of ~~such a~~ the cavity on the signal mode ~~can be~~ is described as a frequency-dependent phase factor~~[15] ,~~ [15] .

$$C(\delta') = \frac{\sqrt{R_1} - \sqrt{R_2}\, e^{i\,\delta'/\nu_f}}{1 - \sqrt{R_1 R_2}\, e^{i\,\delta'/\nu_f}}\;\frac{\sqrt{R_1} - \sqrt{R_2}\, e^{i\,\delta'/\Delta\nu_f}}{1 - \sqrt{R_1 R_2}\, e^{i\,\delta'/\Delta\nu_f}}\,, \tag{2}$$

where $R_{1,2}$ are the reflectivities of M1 and M2, $\cancel{\nu_f}$ $\Delta\nu_f$ the free spectral range of the cavity, and $\delta'/2\pi$ is the detuning from the cavity resonance. For $R_2 = 1$, the

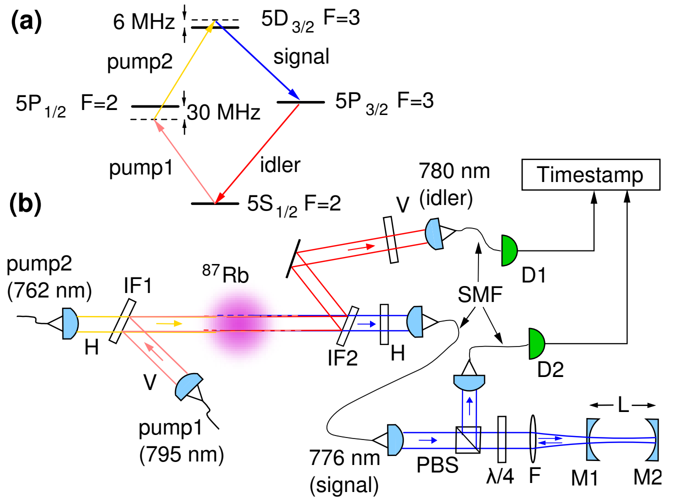

FIG. 1: (a) Cascade level scheme for generation of photon pairs. (b) Schematic of the fourwave mixing experiment in collinear geometry. IF1, IF2: interference filters to combine pump beams and to ~~seperate~~ separate the photons pairs. SMF: Single mode optical fibers. M1, M2: cavity mirrors. Incoming mode s and outgoing mode s' of the cavity are separated by polarising beam splitter (PBS) and a quarter wave plate ($\lambda/4$). D1, D2: silicon avalanche photodiodes (APD).

transformation of the incoming mode ~~becomes~~ is lossless, i.e., $|C(\delta')| = 1$.

The cavity transforms the two-photon wavefunction in Eq. (1) into ~~a new~~ the two-photon wavefunction $\cancel{\tilde{\psi}(t_{s'}, t_i)}$ ~~between photodetection times $t_{s'}, t_i$ in the modified signal and original idler mode according to~~ $\tilde{\psi}(t_s, t_i)$:

$$\tilde{\psi}(t_{\cancel{s'}s}, t_i) = \mathcal{F}_s^{-1}\left[C(\omega_s - \omega_s^0 - \delta)\cdot \mathcal{F}_s\left[\psi(t_s, t_i)\right]\right], \quad (3)$$

where $\mathcal{F}_s$ denotes a Fourier transform from time t_s to frequency $\omega_s/2\pi$, and δ the detuning of the cavity resonance peak from the signal photon center frequency $\omega_s/2\pi$.

If the ringdown time of the cavity matches the coherence time τ of the photon pair in ~~eq~~Eq. (1), ~~then this results in~~ the resulting wavefunction is:

$$\tilde{\psi}(t_{\cancel{s'}s}, t_i) = \frac{A}{\sqrt{1+4\,\delta^2\tau^2}} \left[\, 2\,\delta\,\tau\, e^{\cancel{-(t_i-t_{s'})/2\,\tau}-(t_i-t_s)/2\,\tau}\,\Theta(t_i - t_{\cancel{s'}s}) + e^{\cancel{(t_i-t_{s'})/2\,\tau}(t_i-t_s)/2\,\tau}\,\Theta(-t_i + t_{\cancel{s'}s})\right], \quad (4)$$

with an exponentially rising and an exponentially decaying component. Their relative weight can be controlled by the detuning δ, and for $\delta = 0$, a time-reversed version of ~~eq~~Eq. (1) is obtained:

$$\tilde{\psi}(t_{\cancel{s'}s}, t_i) = A\, e^{\cancel{(t_i-t_{s'})/2\,\tau}(t_i-t_s)/2\,\tau}\,\Theta(-t_i + t_{\cancel{s'}s}). \quad (5)$$

Heralding on the detection of ~~a~~ the modified signal photon, the ~~idler mode assumes~~ resulting idler is a single photon state with a rising exponential envelope, ending at $\cancel{t_i = t_{s'}}\, t_i = t_s$. The cavity thus effects a reversal of the temporal envelope of the heralded idler photons from an exponential decay to a rise.

To experimentally investigate this method, we used the setup shown in Fig. 1. We generate the time-ordered photon pairs by fourwave mixing in a cold ensemble of ^{87}Rb atoms in a cascade level scheme. Pump beams at 795 nm and 762 nm excite atoms from the $5S_{1/2}, F = 2$ ground level to the $5D_{3/2}, F = 3$ level by two photon transition. The 776 nm (signal) and 780 nm (idler) photon pairs are generated by a cascade decay back to the ground level and coupled to single mode fibers. All four modes are ~~aligned collinearly~~ collinear and propagate in the same direction. The coherence time τ of the photon pairs is determined by a time-resolved coincidence measurement between the detection of signal and idler photons to be 5.9 ns. Details about the photon pair source can be found in [16] and [11].

One of the modes of the photon pairs (signal in Fig. 1) is coupled to the fundamental transverse mode of an asymmetric cavity, formed by mirrors M1, M2 with a radius of curvatures of 100 mm and 200 mm, respectively. We charaterize the cavity using a frequency stabilized laser of wavelength 776 nm. The reflectivity of mirror M1 is determined by direct measurement with a PIN photodiode to be $R_1 = 0.9410 \pm 0.0008$. Transmission through the mirror M2 and absorption by the mirrors leads to losses in the cavity. The loss per round trip is determined from the transmission through and the reflection from the cavity and is included in the reflectivity of M2, $R_2 = 0.9982 \pm 0.0010$. The mirrors are seperated by 5.5 cm corresponding to a free spectral range $\cancel{\nu_f}\Delta\nu_f$=2.7 GHz. Therefore, an incident photon of Fourier bandwidth $1/(2\pi\tau) = 27$ MHz interacts effectively with only one longitudinal mode of the cavity, ensuring that Eq. (2) is an ~~adeqate~~ adequate model. The light reflected off the cavity is ~~seperated from~~ separated from the incident mode by using a polarising beam splitter (PBS) and a quarter waveplate ($\lambda/4$).

~~In the absence of the cavity the photon pair Eq. (1)has a decaying exponential envelope as a fuction of the time difference $t_i - t_{s'}$. The transformation of the temporal shape due to the interaction with the cavity is determined~~

We infer the temporal shape of the heralded photons from the time distribution of the coincidence rate $\cancel{G^{(2)}_{s'i}}$ $G^{(2)}_{si}$ between the APDs D1 and D2. ~~The $G^{(2)}_{s'i}$~~ In Fig. 2 we show the $G^{(2)}_{si}$ for three different cavity-photon detunings~~is shown in Fig. 2.~~. When the cavity resonance is tuned ~~about $\delta/2\pi = 120$MHz away from~~ far away from the signal photon frequency ω_s^0, in this case about $\delta/2\pi = 120$ MHz, the temporal envelope remains nearly unchanged ~~as an exponential decay~~ from the exponential decay obtained without cavity and expressed by Eq. (1). At $\delta/2\pi = 27$ MHz, ~~it becomes~~ the time distribution

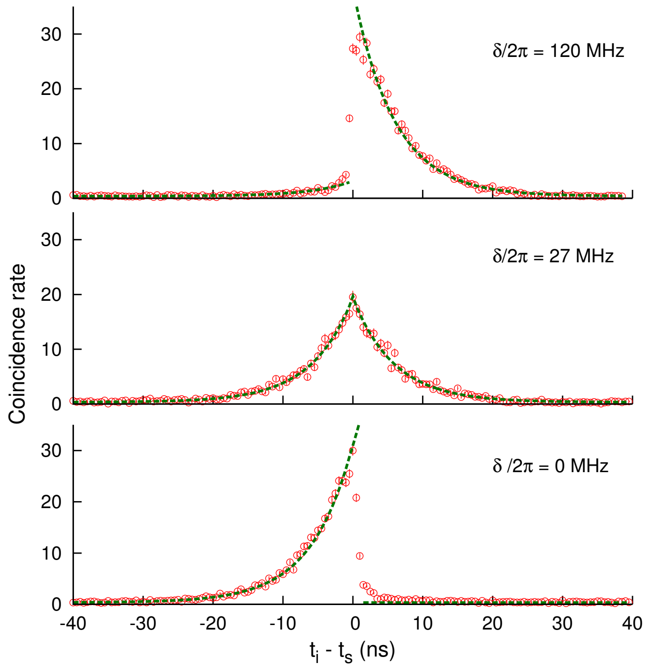

FIG. 2: Transformation of the temporal envelope of the photon pairs from exponential decay to rise. The cavity is aligned in the signal mode. The y-axis shows the coincidence rate $G^{(2)}_{s'i}$ between the detectors D1 and D2 as a function of the detection time difference with a resolution of 0.5 ns. The solid line represents $|\tilde{\psi}(t_{s'}, t_i)|^2$ obtained from the model [Eq. (4)]. The amplitude factor A is the only free parameter used to fit the experimental points.

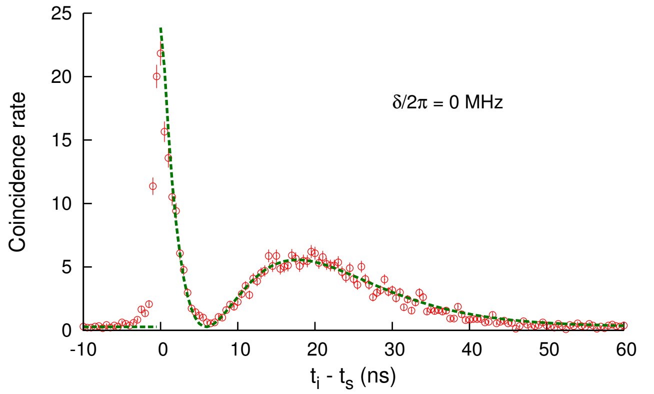

FIG. 3: Temporal envelope of the photon pairs when the cavity is aligned in the idler mode. Solid line represents $|\tilde{\psi}(t_s, t_{i'})|^2$ obtained from the model. The amplitude factor A is the only free parameter used in the fit.

becomes a symmetric exponential, and on resonance~~(~~, $\delta/2\pi = 0$~~), it transforms into~~ , we obtain a rising exponential shape. ~~If the detection of a signal photon is used as a herald, the idler mode now has a single photon with an exponentially rising temporal envelope.In all three cases, the time constant remains unchanged . The change in shape is the result of the frequency dependent~~ For the three detunings the measurement agrees with the shape expected from Eq. 4: the exponential time constants remain unchanged and the new temporal shapes are determined by the phase shift across the cavity resonance ~~Eq.~~as per Eq. (2)~~. We note that the temporal shape of the two photon wavefunction~~ .

The resonant case, Fig. 2(c), is interesting. From the time distribution of the coincidence counts it is evident that the situation is symmetrical to what we presented in [11] : by heralding on the signal photon we now obtain an idler photon with a rising exponential temporal envelope. This result, though predicted by the ~~model Eq. 4fits well with the measured coincidence rate for all three detunings. In the resonant case Fig. 2(c)~~theory, is particularly exciting: the idler photon is resonant with a ground state transition and the obtained temporal envelope is similar to the time reversal of the one obtained by spontaneous decay. The mismatch between the ideal shape and the measured one is in the 7% of the total coincidences that occur after the detection of the herald ($t_i - t_s > 0$). ~~This~~ We attribute this deviation from the predicted shape ~~is due~~ to an imperfect spatial mode matching~~and the loss in the cavity. The loss in the cavity~~ . ~~is proportional to the fraction of incident light that couples to the cavity mode, and is therefore highest when $\delta = 0$. We determine this loss by comparing the total pair rate when $\delta = 0$ and $\delta = 120$MHz to be 5.5.~~

~~We then investigate the effect of having the cavity in the idler mode to the temporal shape of the photon pairs. The cavity resonance is tuned to match the frequency of the idler photons.~~To confirm the predictive power of our model, we repeated the same experiment swapping the roles of the signal and idler modes. From the thoretical point of view, this corresponds to swapping the subscripts s and i in Eqs. (3) and (4). Figure 3 shows the time resolved coincidence rate ~~$G^{(2)}_{si'}$~~ $G^{(2)}_{si}$ between the signal ~~photons and the~~ and modified idler photons ~~from the cavity reflection~~with the cavity tuned to resonance with the idler central frequency. In this case the cavity ~~does not reverse the temporal envelope, but transforms it~~ transforms the exponentially rising temporal envelope into a more complex shape. ~~We use the model described before, but now with the phase shift Eq. applied to the idler mode to obtain the~~ Our model predicts accurately this complex shape, as can be seen from the solid line in ~~Figure~~Fig. 3. ~~It can be seen that the model predicts the shape accurately for this case as well.~~

~~We now show how a photon with "time reversed" envelope significantly improves the interaction with the cavity compared to an exponentially decaying photon of same bandwidth. We are interested in studing this~~

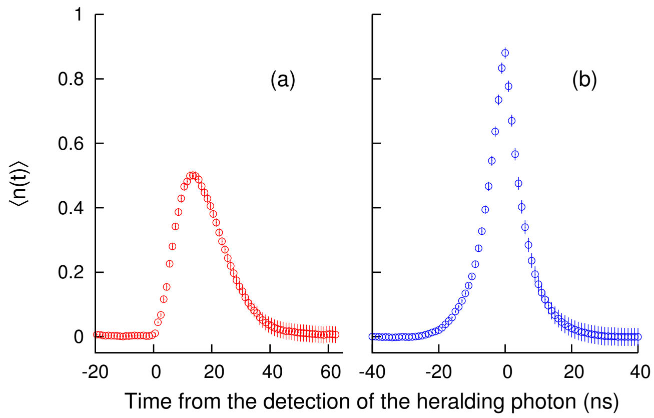

FIG. 4: Mean photon number in the cavity. (a) Cavity is in the idler mode with decaying exponential incident photon. Detection of a signal photon is used as herald. (b) Cavity is in the signal mode with rising exponential incident photon. Detection of an idler photon is used as herald.

~~system because of the analogy proven by [17] between the absorption probability of the photon by a single atom and the mean photon number $\langle n \rangle$ in the cavity.~~

Using the same setup, we observe the different interaction probability of photons with falling and rising exponential time envelope with the cavity.

~~We can~~ The photons that interact with the cavity acquire a time delay with respect to those reflected off M1. We estimate the mean photon number $\langle n(t) \rangle$ as a function of time using an algorithm similar to the one used by [12]~~and by exploiting the strong time correlation of the photon pairs. The photons that interact with the cavity acquire a time delay with respect to those that are reflected off M1. We can evaluate $\langle n(t) \rangle$ by comparing the time~~: we compare the time distributions of coincidence rates $G^{(2)}_{fr}$ and $G^{(2)}_{or}$ when the cavity is tuned respectively far-off resonance ~~and on resonance with the photons.~~

$$\langle n(t) \rangle = \frac{e^{-\eta t \Delta} \int_{-100}^{t} \left[G^{(2)}_{fr}(t') - G^{(2)}_{or}(t') \right] e^{\eta t \nu_f} \mathrm{d}t'}{\int_{-100}^{100} G^{(2)}_{fr}(t') \mathrm{d}t'}$$

~~where $G^{(2)}_{fr}$ and $G^{(2)}_{or}$ are the coincidence rates when~~ ($\delta/2\pi = 200\,\mathrm{MHz}$~~and~~) and on resonance ($\delta/2\pi = 0\,\mathrm{MHz}$~~respectively.~~) with the incident photons,

$$\langle n(t) \rangle = \frac{e^{-\eta t \Delta} \int_{-\infty}^{t} \left[G^{(2)}_{fr}(t') - G^{(2)}_{or}(t') \right] e^{\eta t \nu_f} \mathrm{d}t'}{\int_{-\infty}^{\infty} G^{(2)}_{fr}(t') \mathrm{d}t'}. \quad (6)$$

We use the total coincidence rate ~~in ±100ns time window~~ when far-off resonance as normalization factor. ~~The term $\eta = (1 - R_2)$ includes both the round trip loss~~ We estimated η, that includes the cavity losses per round trip and transmission through M2~~.~~, to be 5.5% by comparing the total pair rate when the cavity is tuned on and far off resonance.

When the cavity is aligned in the idler mode, a heralded single photon with decaying exponential envelope ~~interact~~ interacts with the cavity~~. The~~: the mean photon number in the cavity reaches a maximum of 0.50 ± 0.01. On the other hand, when the cavity is aligned in the signal mode we have a heralded single photon with increasing exponential envelope interacting with the cavity~~. In~~; in this case, $\langle n(t) \rangle$ reaches a maximum of 0.88 ± 0.02.

As expected, the photon with the rising exponential waveform interacts more efficiently with the cavity. Following the analogy proven in [17], we expect this result to be extended to the probability of ~~absoption~~ absorption of a single photon by a single atom. In the case of interaction with a single atom, it will be necessary to also match the bandwidth of the transition. We have already demonstrated how it is possible to control the bandwidth of the photon generated by the cascade process by adjusting the optical density of the atomic medium [16] .

In summary, we have demonstrated a method to transform an heralded single photon with a decaying exponential temporal envelope to a rising exponential envelope using a cavity. Using this method, we obtain single photons that resembles the time reversal of the photons from the spontaneous decay process resonant to the D1 line of ^{87}Rb atoms. We have also shown how a single photon with a rising exponential envelope interacts strongly with a single mode of a resonant cavity.

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