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CMT

Theoretical Description of Time-Bin Entangled Photons from a Semiconductor Quantum Dot

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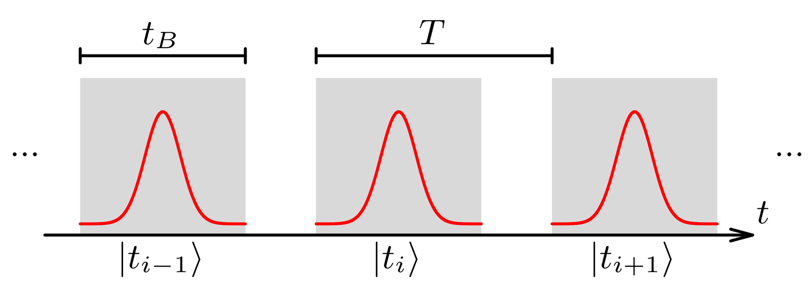
DFG Deutsche Forschungsgemeinschaft

Introduction

Instead of Entanglement in the Polarization of the light, it is also possible to entangle photons in time
For this, the time is sectioned in consecutive time-bins $|t_i\rangle$ of width t_B, spaced by a time T.
This features several advantages for fibre-based communication:

- fibres do not need to be polarization-maintaining, existing infracstructure could be used
- vibrations or temperature fluctuations that lead to dephasing of the polarization do not matter
- however, precise synchronization is necessary



⇒ **How can time-bin entangled photons be created and how can we theoretically describe them?**

Systems for generating timebin-entangled photons

Several schemes exist for creating time-bin entangled photon pairs, including spontaneous four-wave mixing in fibres, or spontaneous parametric down-conversion to create the photon pairs.
However, these approaches **can not create time-bin entangled photons on-demand**

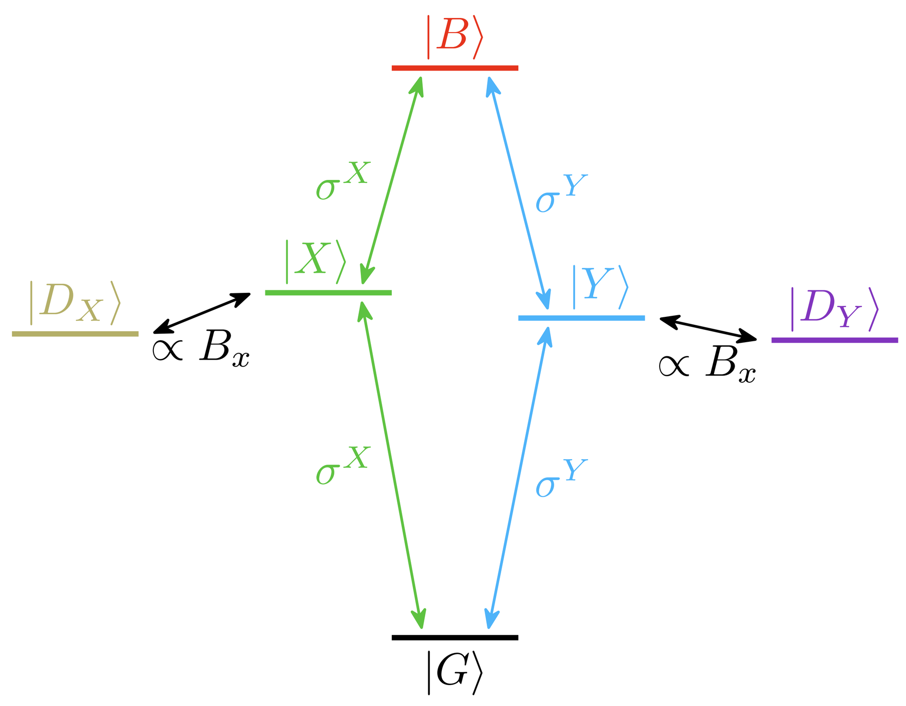
In general, two time bins are of interest, which are labelled **early (E) and late (E)**. The desired entangled **two-photon state** is

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|EE\rangle + |LL\rangle)\,.$$

In this state, the photon pair is either present in the early or the late time-bin, but never distributed about both.

Here, we want to focus on the creation of photon pairs using a **semiconductor quantum dot (QD) as a photon pair source**.

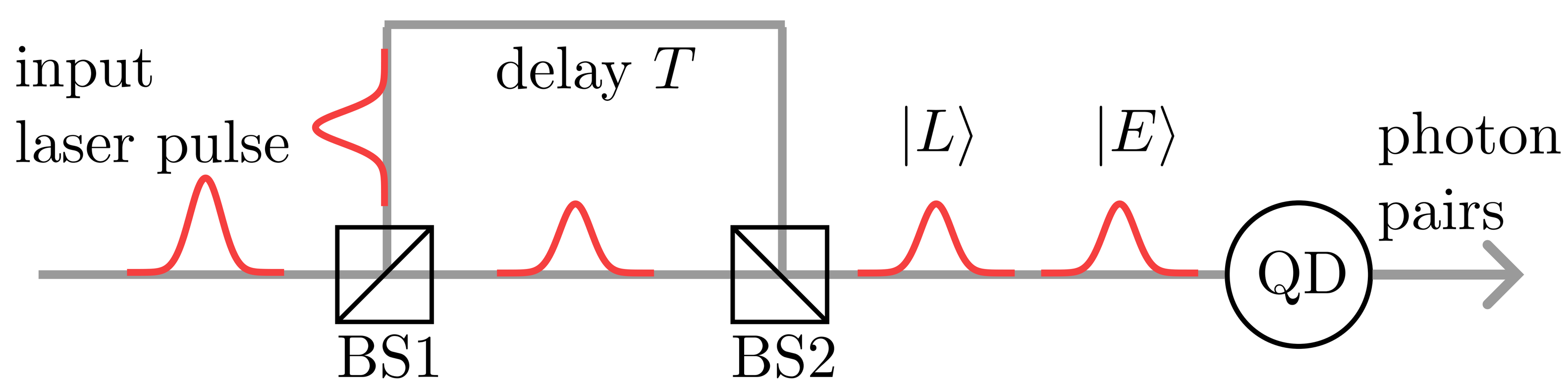
- QD can be modelled as a six-level system
- features two bright excitons X, Y, biexciton state B and two dark excitons D_X, D_Y
- bright excitons are controlled using pulsed lasers
- photon pairs are created in the biexciton-exciton cascaded emission
- spin-selection rules suppress optical transitions to dark states
- dark states can be coupled with a magnetic field



Using this system, time-bin entangled photons can be created using different approaches.

Probabilistic approach

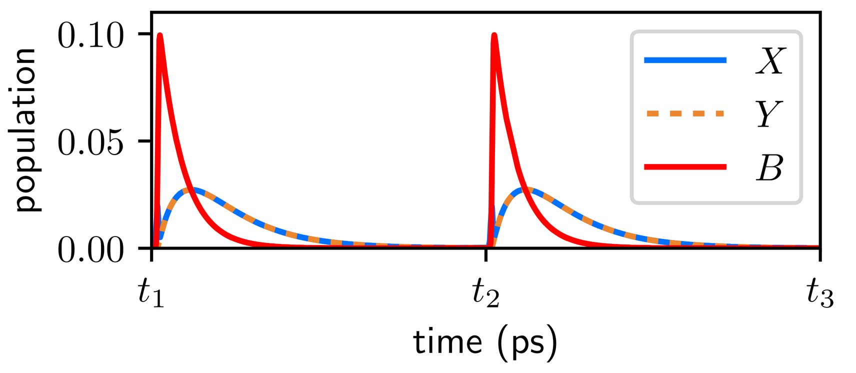
- In this scheme, time-bin entangled photon pairs are created using **two consecutive two-photon excitation processes with a low preparation fidelity** Nat Commun **5**, 4251 (2014)
- The low preparation fidelity is necessary, as the probability to re-excite the quantum dot, leading to four photons in total, needs to be as low as possible.



- the input laser pulse is split, one of the parts is delayed by the time-bin separation T
- early and late pulse both excite the quantum dot, leading to photon pair generation
- if a single pulse excites $|B\rangle$ with probability p_1, the chance to get four photons is p_1^2
  ⇒ for $p_1 = 10\,\%$, $p_1^2 = 1\,\%$ and the probability for the desired two-photon state is $2p_1(1-p_1) = 18\,\%$

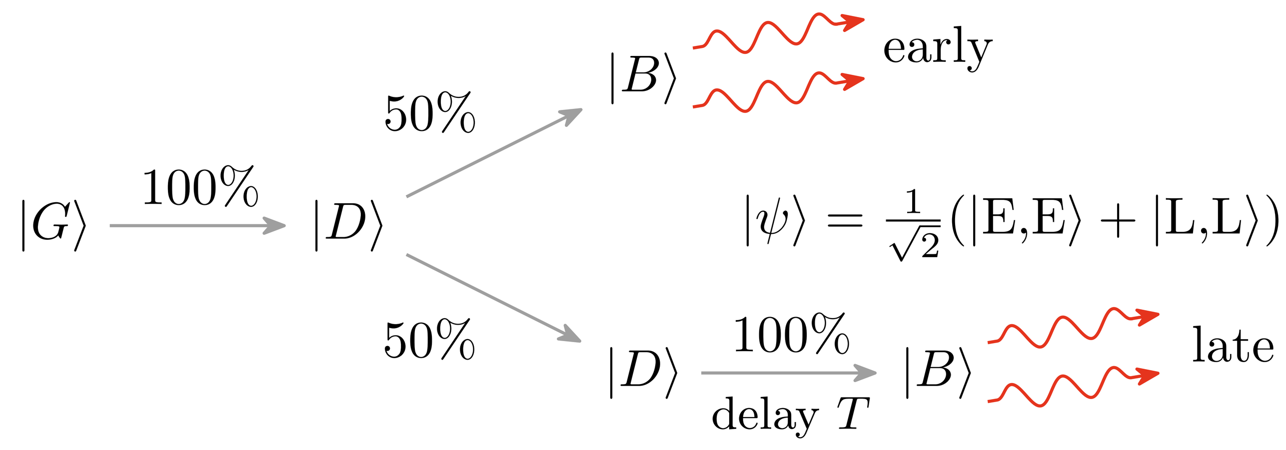
- simple to use excitation protocol
- in most of the cases, no photon is emitted

→ **on-demand generation not possible!**



Using the dark exciton

- Time-bin entangled photon pairs can be produced relying on the metastable dark states in quantum dots. Applying a tilted magnetic field of $B_x \sim 3\,\mathrm{T}$ leads so sufficient brightening of these states
- The scheme is a **multi-step process starting in the dark state:**



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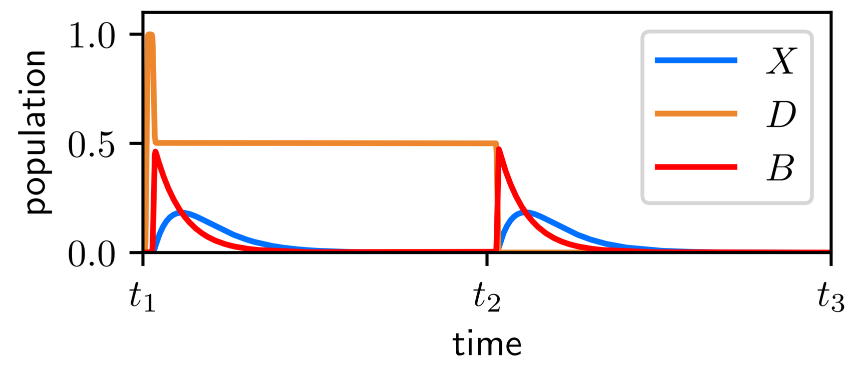
- First, the population is transferred to the dark state using for example chirped excitation
- next, a superposition of equal parts $|D\rangle$ and $|B\rangle$ has to be prepared
- the time-bin separation T is chosen such that the biexciton decays completely
- the rest of the population stored in $|D\rangle$ is transferred to $|B\rangle$

- experimentally more challenging
- using the dark state ensures emission of exactly one photon pair

→ **on-demand generation!**



Theoretical description of the photon density matrix

- For the calculation of the photon density matrix, we simulate multi-time correlation functions of the transition operators $\sigma_{b,x}$, that correlate the events in different time-bins.
- $\sigma_b = |X\rangle\langle B| + |Y\rangle\langle B|$ ($\sigma_x = |G\rangle\langle X| + |G\rangle\langle Y|$) is the source of the electric field that corresponds to the emission of a biexciton (exciton) photon.
- the operators depend on the time-bin *early* or *late*, i.e., $\sigma^E_{b/x} = \sigma_{b/x}(t), \sigma^L_{b/x} = \sigma_{b/x}(t+T)$
- with $i,j,k,l \in E, L$, the two-photon density matrix is calculated using

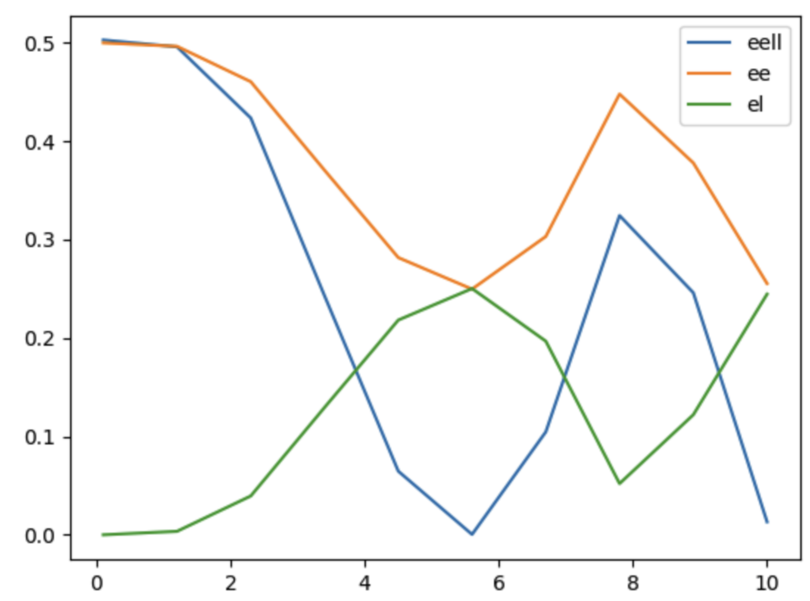
$$\rho^{2p}_{ij,kl} = \frac{\overline{G}^{(2)}_{ij,kl}}{\mathrm{Tr}\left\{\overline{G}^{(2)}\right\}}$$

- special care has to be given to the time-ordering of the operators:

$$\overline{G}^{(2)}_{ij,kl} = \int_0^{t_B} dt_1 \int_0^{t_B} dt_2 \,\langle \mathcal{T}^- \left[\sigma_B^{i\,\dagger}(t_1)\sigma_X^{j\,\dagger}(t_2)\right] \mathcal{T}^+ \left[\sigma_X^l(t_2)\sigma_B^k(t_1)\right]\rangle$$

- $\mathcal{T}^-$ orders the smallest time argument to the left, $\mathcal{T}^+$ to the right

- For the case of two delayed two-photon excitations, the concurrence and photon yield is shown depending on the pulse area
- only for very small pulse areas, a good entanglement can be achieved
- however, this goes in hand with a low photon yield
- **for the deterministic scheme, the concurrence is XX with a considerably higher photon rate!**



Conclusions

- on-demand generation of time-bin entangled photon pairs is a challenging task, but if achieved, it has many potential advantages over polarizaiton entanglement
- exciting the QD twice with a delay T can lead to time-bin entangled photons, however this is **not deterministic** and features only a **low efficiency**
- **using the dark exciton enables highly efficient, on-demand generation of time-bin entangled photon pairs**

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