Emitter-based photonic entanglement generation

Paul Hilaire

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Experimental paper

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Deterministic and reconfigurable graph state generation with a single solid-state quantum emitter

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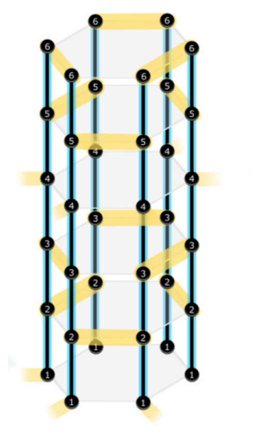
Joint work between CNRS-C2N and Quandela

Theory papers



Near-deterministic hybrid generation of arbitrary photonic graph states using a single quantum emitter and linear optics

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A Spin-Optical Quantum Computing Architecture

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Tailoring Fusion-Based Photonic Quantum Computing Schemes to Quantum Emitters

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Why photons?

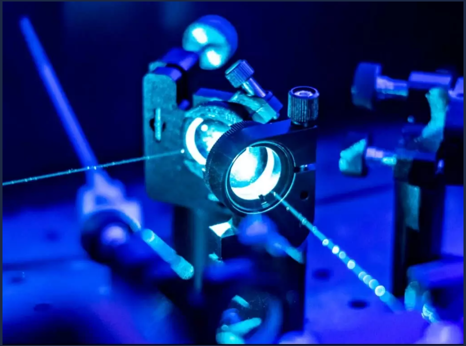


Figure: Photon qubits: robust, fast, long-distance

- Ubiquitous platform for Q. communications & computing
- Advantages:
  - Virtually no decoherence
  - Fast operation time
  - Long-range transmission
- Challenges:
  - Photon loss
  - No deterministic entangling gates (DV regime)

Quantum Computing with Photons

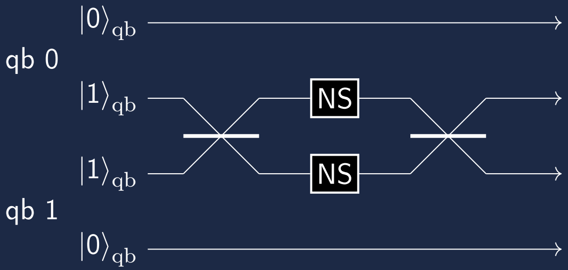
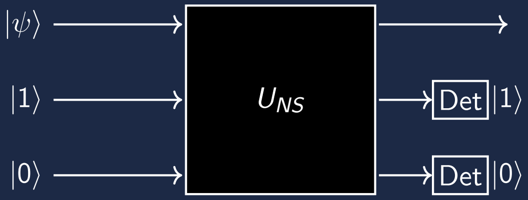


Figure: Probabilistic CZ gate. (Success probability 2/27). NS=Nonlinear Sign shift: Use 1 photon + 2 modes as ancillas, success 1/4

- No deterministic CNOT in linear optics

From gates to resource states



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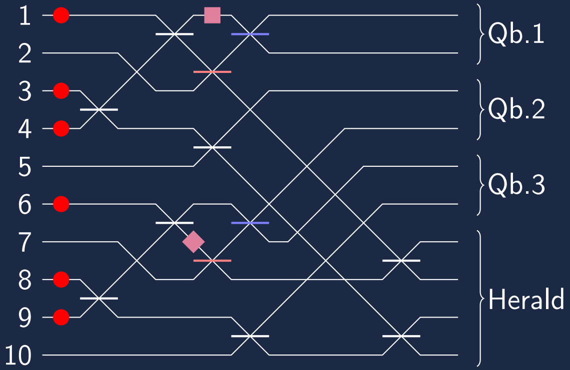

Figure: Optical circuit for $|\mathrm{GHZ}_3\rangle$ generation (Success proba 1/32). (Bell generation 1/4)

- No deterministic CNOT in linear optics
- **Solution:** Replace gates with entangled state generation

From gates to resource states

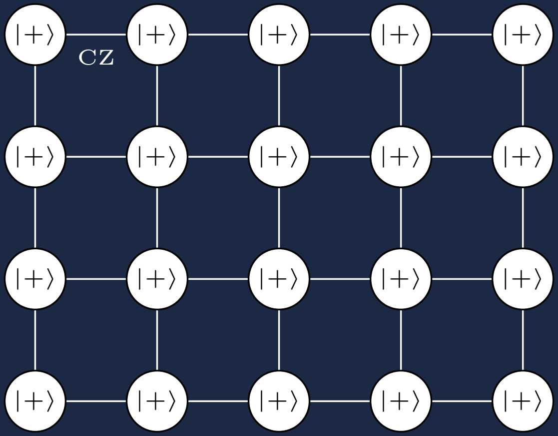

Figure: Graph state lattice $|G = (V, E)\rangle$

- No deterministic CNOT in linear optics
- **Solution:** Replace gates with entangled state generation
- Measurement-based QC:
  - Generate large entangled state (hard)
  - Measure qubits (easy)
- Graph states: key resource

From gates to resource states

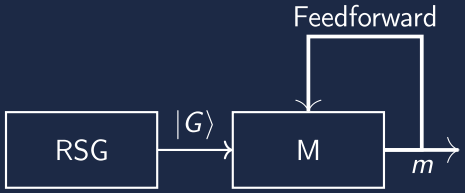

Figure: Measurement-based QC

- No deterministic CNOT in linear optics
- **Solution:** Replace gates with entangled state generation
- Measurement-based QC:
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  - Measure qubits (easy)
- Graph states: key resource

From gates to resource states

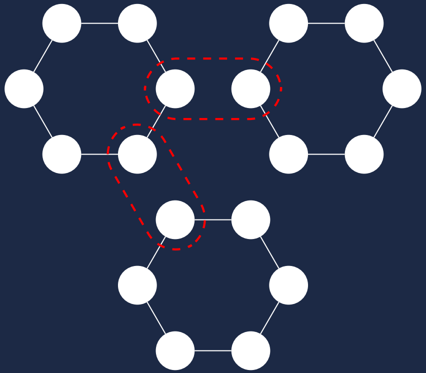

Figure: Fusion Based QC general ideas. (Fusion prob $1 - 1/2^n$)

- No deterministic CNOT in linear optics
- **Solution:** Replace gates with entangled state generation
- Measurement-based QC:
  - Generate large entangled state (hard)
  - Measure qubits (easy)
- Graph states: key resource
- Fusion-based QC: smaller resource states + Bell measurements

Graph States

What are graph states?

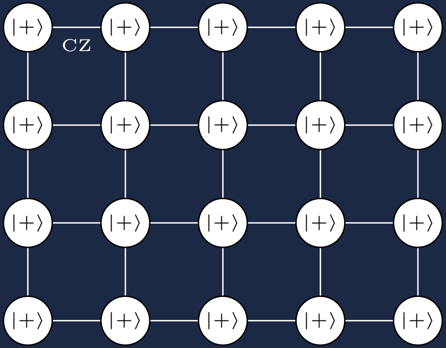

Figure: Graph state $|G\rangle$, with $G = (V, E)$

- Quantum state in 1-to-1 correspondence with a graph $G = (V, E)$.
- Vertices $v \in V$ = qubits $|+\rangle$.
- Edges $(v, v') \in E = CZ$ gates.

$$|G = (V, E)\rangle = \left(\prod_{(v,v') \in E} CZ_{v,v'} \right) \otimes_{v \in V} |+\rangle_v$$

Stabilizer properties:

$$\forall v \in V, \quad \left(X_v \prod_{(w,v) \in E} Z_w \right) |G\rangle = +|G\rangle$$

What are graph states?

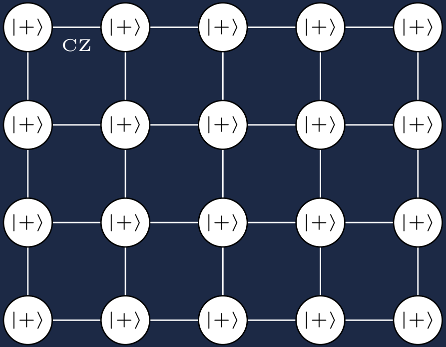

Figure: Graph state $|G\rangle$, with $G = (V, E)$

- Universal resource for QC / for Fault Tolerant QC
  - Paradigm particularly well-suited for photonics
  - But not only! (resilience against erasures / coherent errors)
- Applications in quantum communications:
  - Quantum Routing.
  - All-photonic quantum repeaters.
- Quantum cryptography:
  - Native framework for primitives in quantum crypto.
  - Delegated universal blind quantum computing.

Resource State Generation

The "black box" challenge

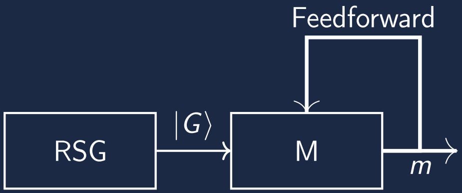

Figure: What is inside RSG???

- To get a resource state (near-) deterministically:
    - Single-photon sources
    - Probabilistic entanglement generation
    - Build larger states.

Deterministic single-photon sources

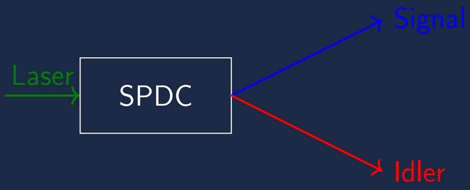

Figure: SPDC source (heralded)

SPDC sources

- Mature, probabilistic ($p \ll 1$)

Deterministic single-photon sources

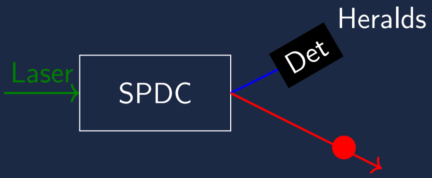

Figure: SPDC source (heralded)

SPDC sources

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- Heralded: detection of idler $\rightarrow$ signal photon

Deterministic single-photon sources

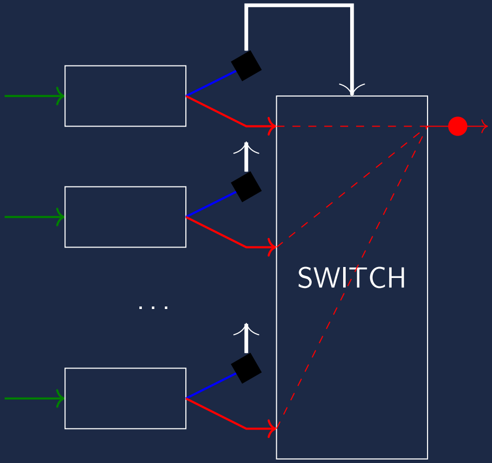


Figure: Multiplexed SPDC sources

SPDC sources

- Mature, probabilistic ($p \ll 1$)
- Heralded: detection of idler $\rightarrow$ signal photon
- Multiplexing:
  - N sources in parallel
  - Fast optical switches
  - Success probability: $1 - (1 - p)^N \approx 1$
- Lead to resource overhead

(Near-)Deterministic entanglement with photons

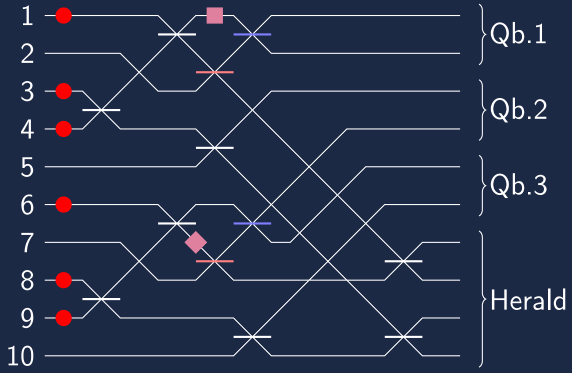
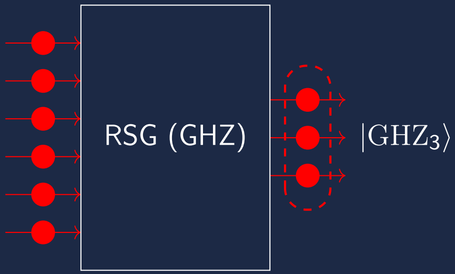


Figure: 3-GHZ generation: $p = 1/32$.

Each red circle requires multiplexed sources

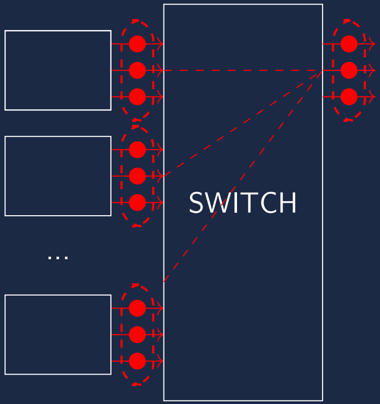
(Near-)Deterministic entanglement with photons



Each red circle requires multiplexed sources

- Generating entanglement: probabilistic
- Larger resource states, smaller success probability
- Even more multiplexing
- Daunting resource overhead

(Near-)Deterministic entanglement with photons



Each red circle requires multiplexed sources

- Generating entanglement: probabilistic
- Larger resource states, smaller success probability
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Ways around:

- Software solution: Optimize generation processes
- **This work:** Circumvent these issues through hardware solution

Quantum Emitters

Deterministic photon sources

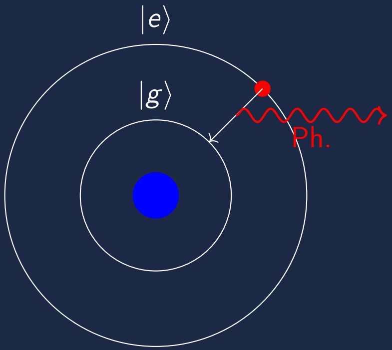

Figure: Scheme of the energy levels of an atom

- Replace SPDC + multiplexing
- Single atom/artificial atom
- Advantages:
  - Deterministic
  - High fidelity
  - Scalable

Deterministic photon sources

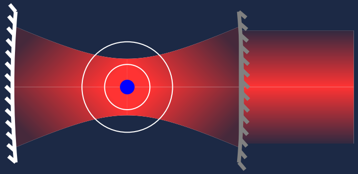

Figure: Atom embedded in an optical cavity. Directional emission

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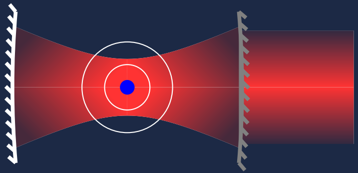
Deterministic photon sources



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Deterministic photon sources

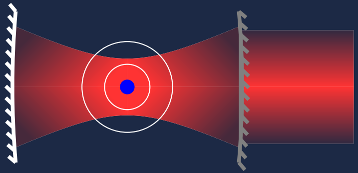
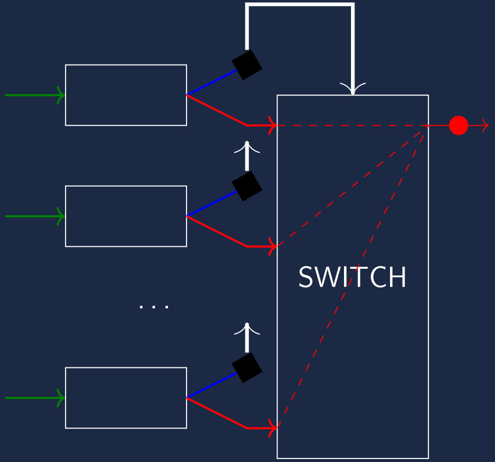
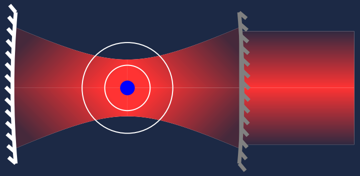


Figure: Atom embedded in an optical cavity. Directional emission

Replace





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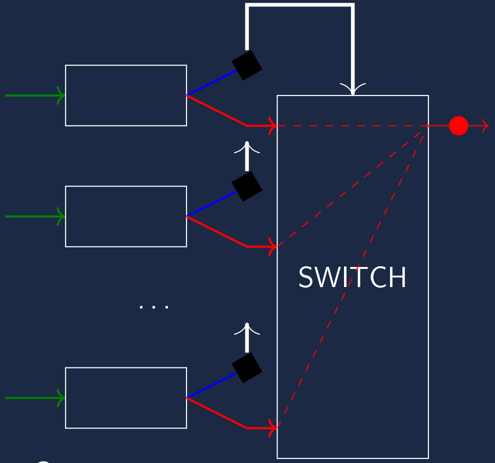
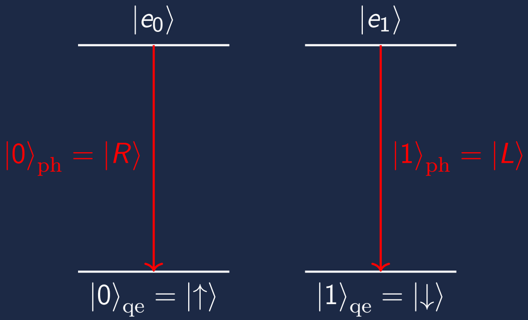
Replace

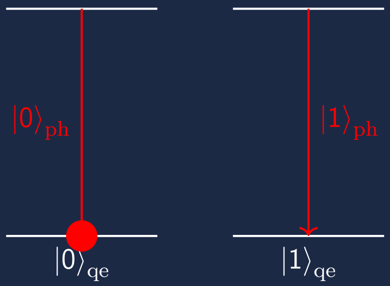


Can we do more?

Source of entangled photons

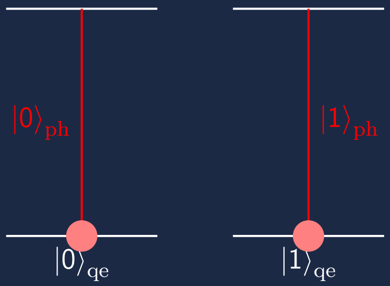


Source of entangled photons



Initialize:

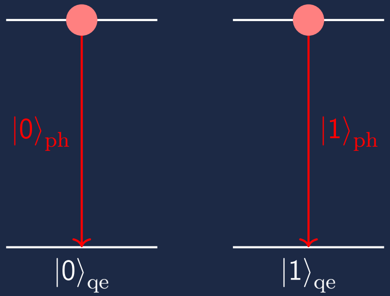
$|0\rangle_{qe}$



Quantum superposition:

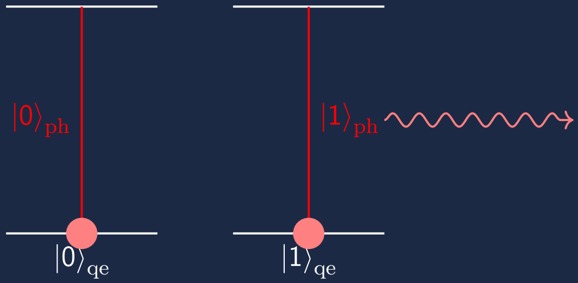
$$|+\rangle_{\mathrm{qe}} = |0\rangle_{\mathrm{qe}} + |1\rangle_{\mathrm{qe}}$$

Source of entangled photons



Excite:

$$|e_+\rangle_{\mathrm{qe}} = |e_0\rangle_{\mathrm{qe}} + |e_1\rangle_{\mathrm{qe}}$$



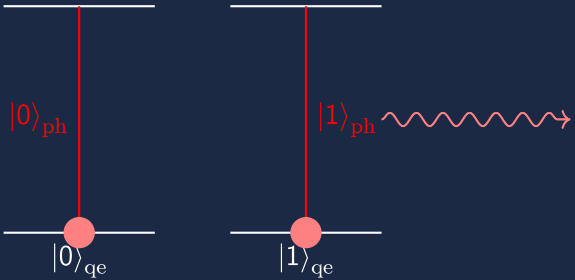
Photon emission (entanglement):

$$|\psi\rangle = |0\rangle_{\mathrm{qe}} \otimes |0\rangle_{\mathrm{ph}} + |1\rangle_{\mathrm{qe}} \otimes |1\rangle_{\mathrm{ph}}$$

$$E_{\mathrm{ph}} = |0\rangle_{\mathrm{ph}} |0\rangle_{\mathrm{qe}} \langle 0|_{\mathrm{qe}} + |1\rangle_{\mathrm{ph}} |1\rangle_{\mathrm{qe}} \langle 1|_{\mathrm{qe}}$$

$$|\psi\rangle = E_{\mathrm{ph}} |+\rangle_{\mathrm{qe}}$$

Source of entangled photons



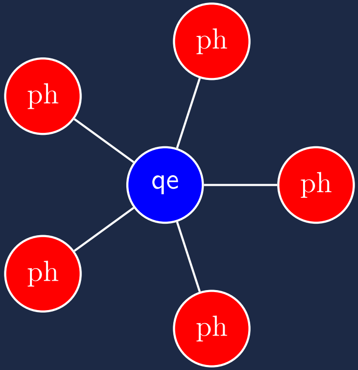
Repeat n times:

$$E_{\mathrm{ph}}{}^{n}\,|+\rangle_{\mathrm{qe}} = |0\rangle_{\mathrm{qe}} \otimes |0\rangle_{\mathrm{ph}}^{\otimes n} + |1\rangle_{\mathrm{qe}} \otimes |1\rangle_{\mathrm{ph}}^{\otimes n}$$

Deterministic source of GHZ states

Source of entangled photons

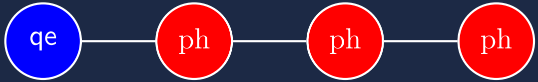
$$|GHZ_n\rangle = {E_{\text{ph}}}^n |+\rangle_{\text{qe}}$$



Up to H on photons

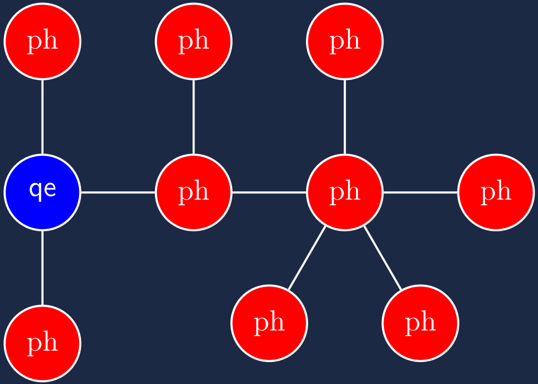
Source of entangled photons

$$|LC_n\rangle = (H_{\mathrm{qe}} E_{\mathrm{ph}})^n |+\rangle_{\mathrm{qe}}$$



Source of entangled photons

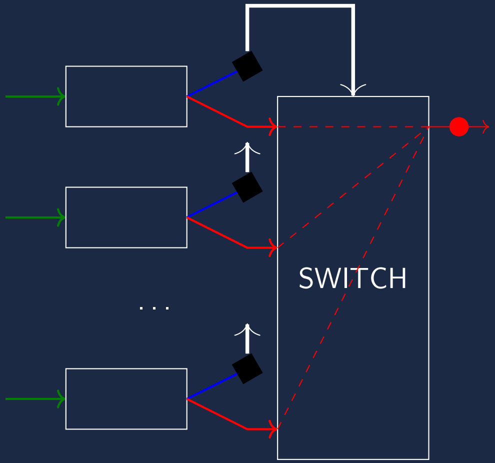
Caterpillar graph states

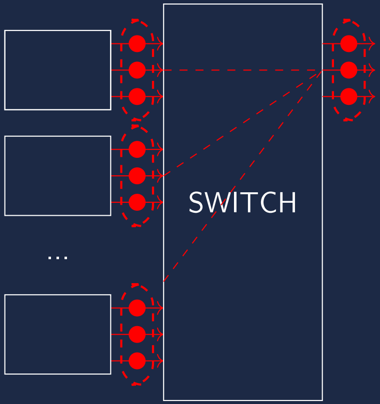


Most general graph that can be produced by a single quantum emitter [1]

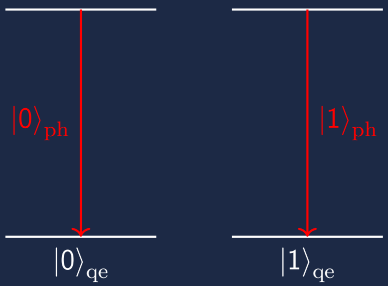
[1] B. Li et al., NPJ QI (2023)

Replacing complex linear-optics by advanced sources





Replacing complex linear-optics by advanced sources



Replacing complex multiplexed linear-optics elements with advanced sources.

Experiments

The quantum emitter

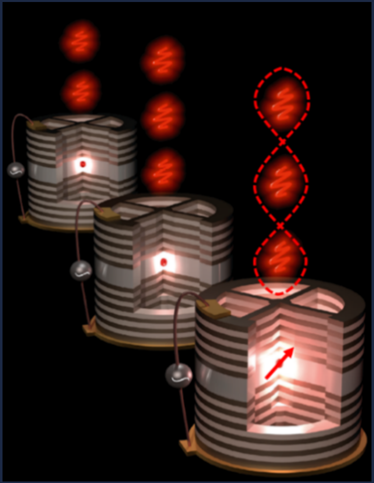
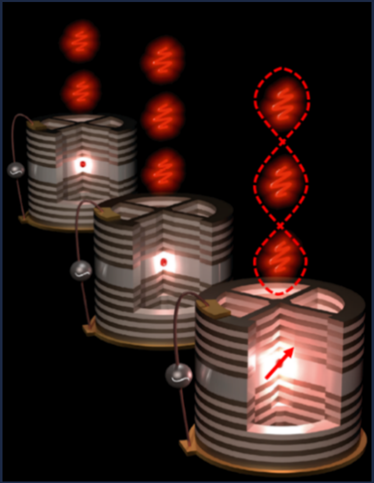


Figure: Quantum dot light source

Single-photon source

- Quantum dots: good artificial atom
- In cavity (enhanced light-matter interaction)
- Produce indistinguishable photons

The quantum emitter



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Level structure

- Electron / hole spin trapped inside the QD
- Desired level structure

The quantum emitter

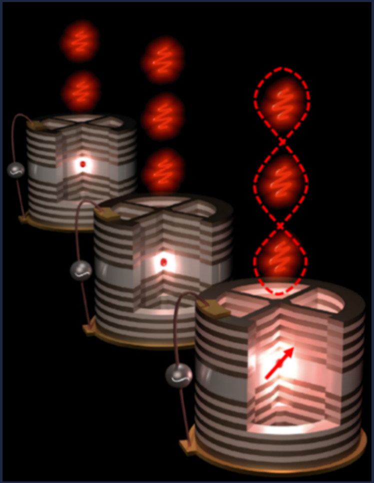


Figure: Quantum dot light source

Single-photon source

- Quantum dots: good artificial atom
- In cavity (enhanced light-matter interaction)
- Produce indistinguishable photons

Level structure

- Electron / hole spin trapped inside the QD
- Desired level structure

Spin quantum control

- Magnetic field precession (Y rotation)
- Optical pulse (Z rotation)
- Full SU(2) control

The quantum emitter

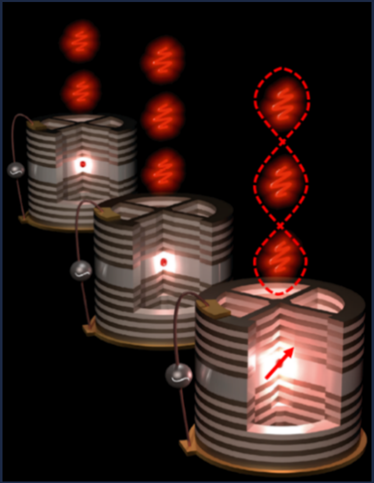
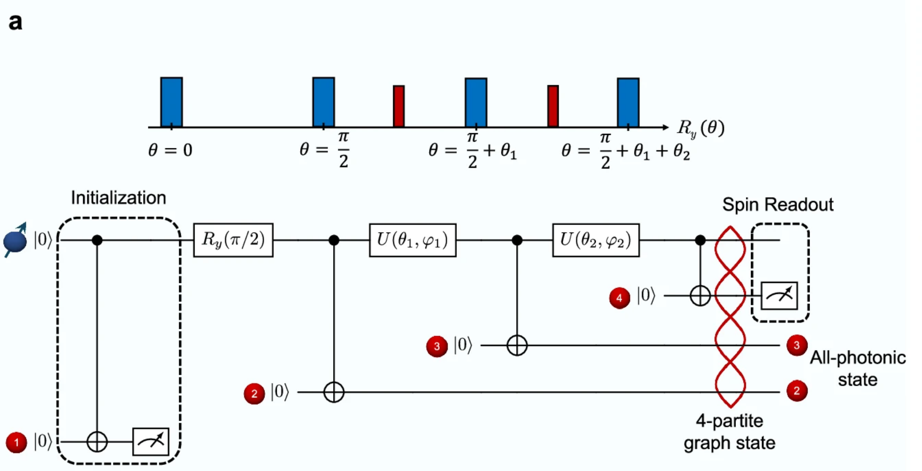


Figure: Quantum dot light source

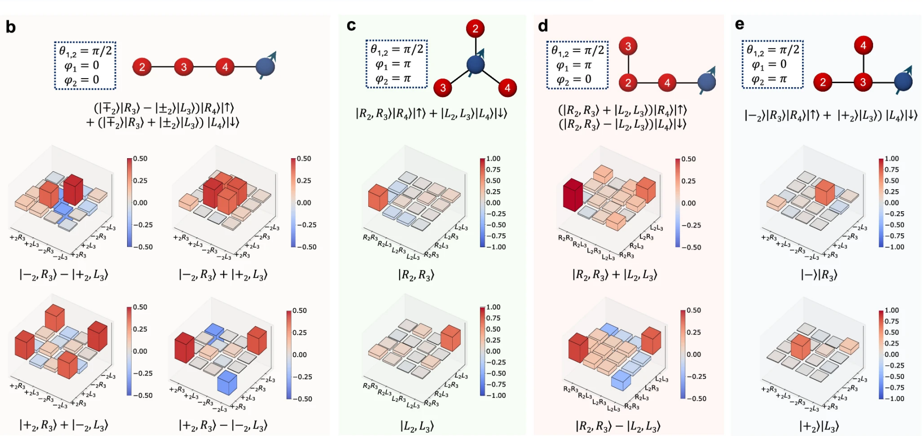
- Deterministic generation of good single-photon sources based on quantum dots [a]
- Getting quantum dot source with excellent light properties [b]
- Trap the desired charge state in QDs [c]
- Linear-cluster state demonstration [d]
- **This work:** Flexible generation of catterpilar graphs [e]

[a] A. Dousse et al., Phys. Rev. Lett., 101, 267404 (2008)
[b] N. Somaschi et al., Nat. Photon., 10, 340 (2016)
[c] P. Hilaire et al., Phys. Rev. B 102, 195402 (2020)
[d] N. Coste et al., Nat. Photon., 17, 582 (2023)
[e] H. Huet et al., Nat. Comm, 16, 4337 (2025)

Experiment


a
$\theta = 0$
$\theta = \frac{\pi}{2}$
$\theta = \frac{\pi}{2} + \theta_1$
$\theta = \frac{\pi}{2} + \theta_1 + \theta_2$
$R_y(\theta)$
Initialization
$|0\rangle$
$R_y(\pi/2)$
$U(\theta_1, \varphi_1)$
$U(\theta_2, \varphi_2)$
Spin Readout
4
3
2
1
All-photonic state
4-partite graph state

Experiment



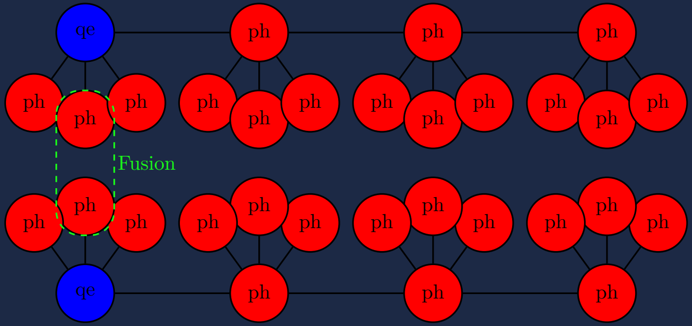
Fidelity $\approx 80\%$

What's next?

What's next?

Experimentally

- Improve the coherence time
- Increase the size of the graph
- Go beyond caterpillar states



Fusion Gates

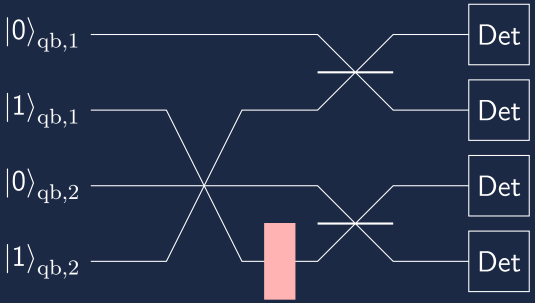


Figure: Fusion gate (Bell measurement)

Succeeds with probability $1/2$.

Ancilla-assisted fusions

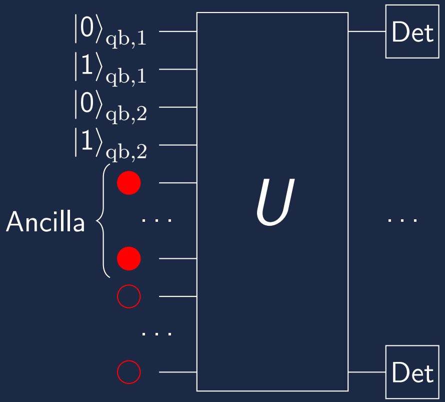
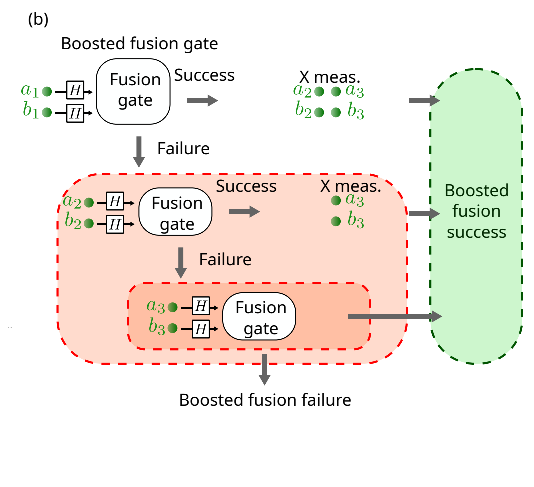
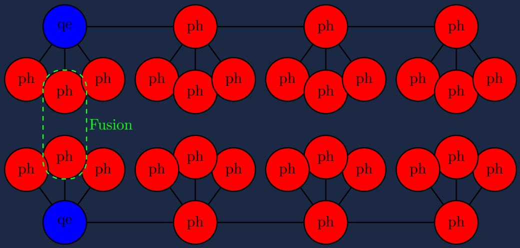


Figure: Ancilla-assisted fusion

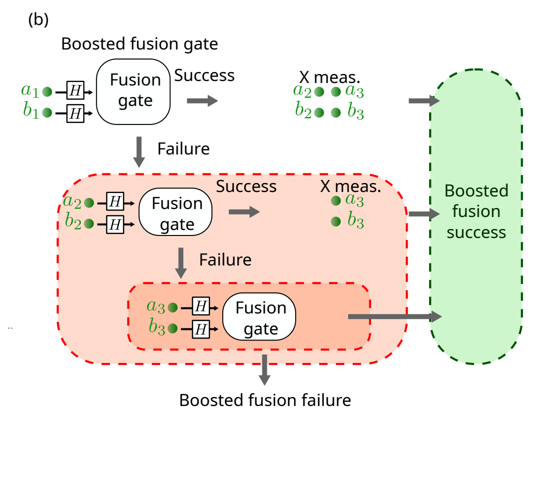
Success probability increased $1 - 1/2^n$ (for $2^n - 2$ ancilla photons)

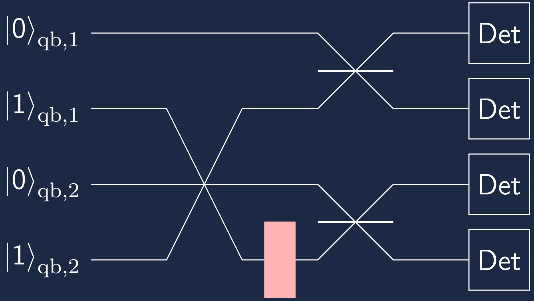
Boosted Fusion Gates



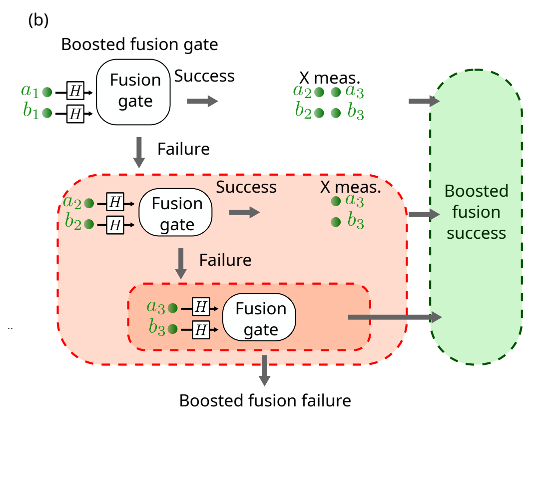


Boosted Fusion Gates



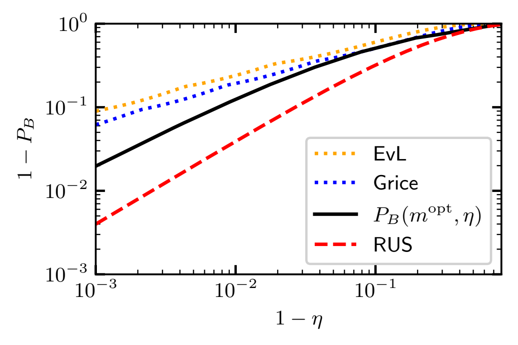


Boosted Fusion Gates



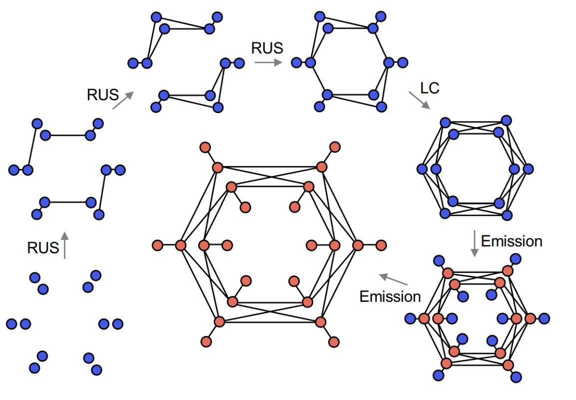
Larger success rate:

$$P_b = \left(1 - \frac{1}{2m}\right)\eta^{2m}$$



Recent result on resource optimisation [2]

How many single-photon source to produce a resource state?
(Shor-(2,2) encoded 6-ring graph state)



[2] S. Wein et al., ArXiv 2412.08611 (2024)

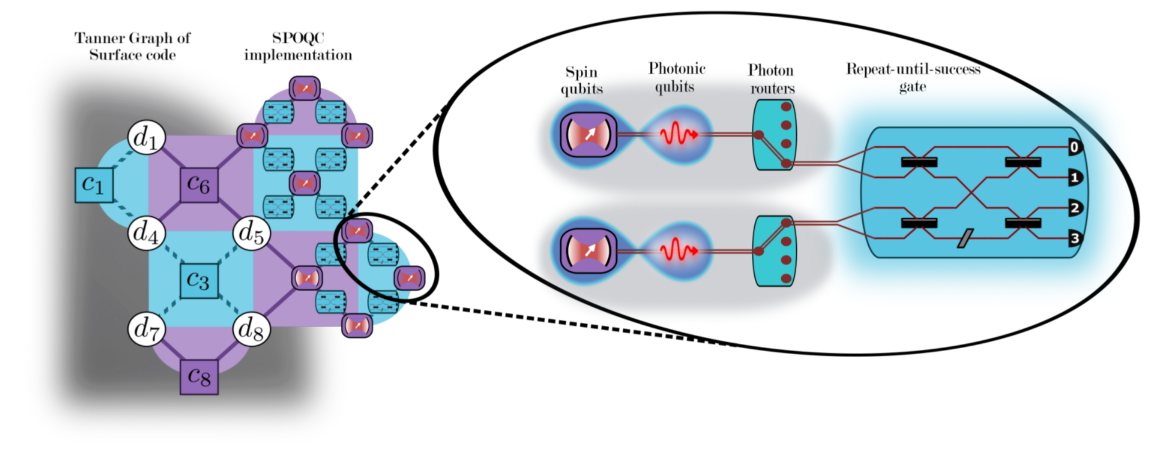
Recent result on resource optimisation [2]

How many single-photon source to produce a resource state?
(Shor-(2,2) encoded 6-ring graph state)

Source type	# Photon source	Loss/comp
Heralded SPS, $p_s = 0.005$	423400	0.22%
Heralded SPS, $p_s = 0.25$	8468	0.22%
Deterministic SPS	2117	0.26%
Caterpillar	28	0.65%
RUS	12	7.5%

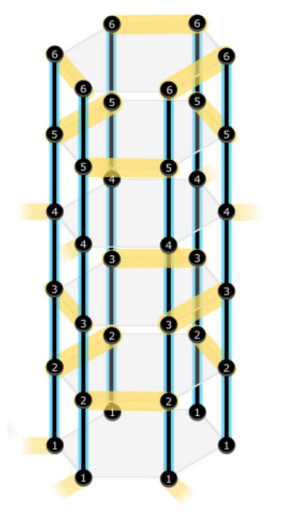
[2] S. Wein et al., ArXiv 2412.08611 (2024)

FTQC architectures: Spin-Optical Quantum Computing [3]



[3] G. de Gliniasty et al., Quantum 8, 1423 (2024)
T. Dessertaine et al., ArXiv 2410.07065 (2024)

FTQC architectures: FBQC with spin-entangled graph states [4]



[4] ML. Chan et al., PRX Quantum 6, 020304 (2025)

Conclusion

- Spin-entangled photon emission reduces drastically the resource overhead in photonic QC
- It also increases the success rate of entangling operations in photonics.
- Can be integrated in fault-tolerant architectures
- How to best use them in hybrid spin-photon architectures?