

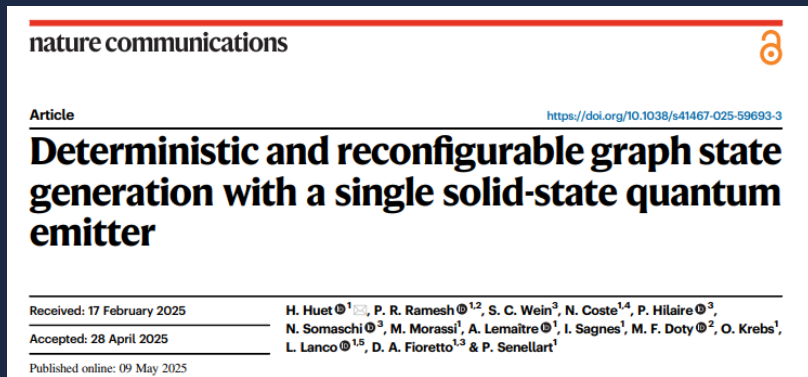
Emitter-based photonic entanglement generation

Paul Hilaire

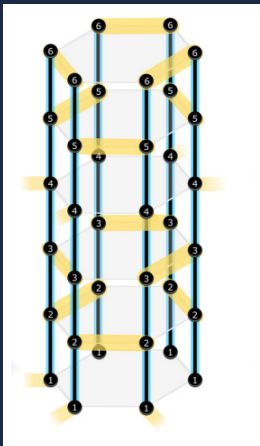
October, 9 (2025)



Inria



Joint work between CNRS-C2N and Quandela



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

Paul Hilaire^{1,2}, Leonid Vidro³, Hagai S. Eisenberg³, and Sophia E. Economou¹

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²Huygens-Kamerlingh Onnes Laboratory, Leiden University

³Racah Institute of Physics, Hebrew University of Jerusalem, 91904 Jerusalem, Israel

A Spin-Optical Quantum Computing Architecture

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²Sorbonne Université, CNRS, LIP6, F-75005 Paris, France

Tailoring Fusion-Based Photonic Quantum Computing Schemes to Quantum Emitters

Ming Lai Chan^{1,2,*}, Thomas J. Bell^{3,4,†}, Love A. Pettersson¹, Susan X. Chen^{4,5}, Patrick Yard³, Anders S. Sørensen¹, and Stefano Paesani^{1,5,†}

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⁵NNF Quantum Computing Programme, Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark

Why photons?

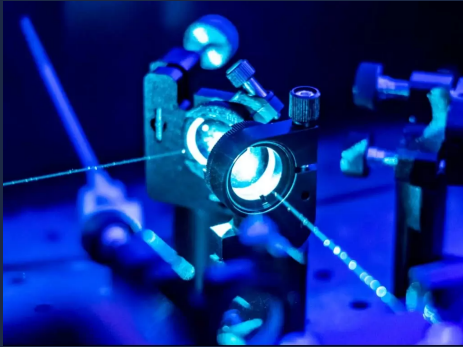
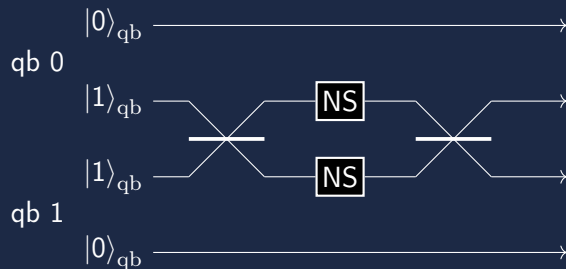


Figure: Photon qubits: robust, fast, long-distance

- 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

From gates to resource states



- No deterministic CNOT in linear optics

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

From gates to resource states

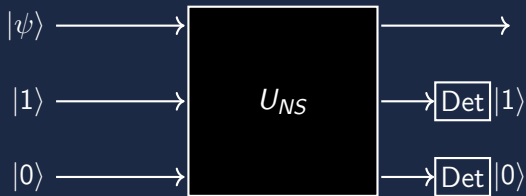
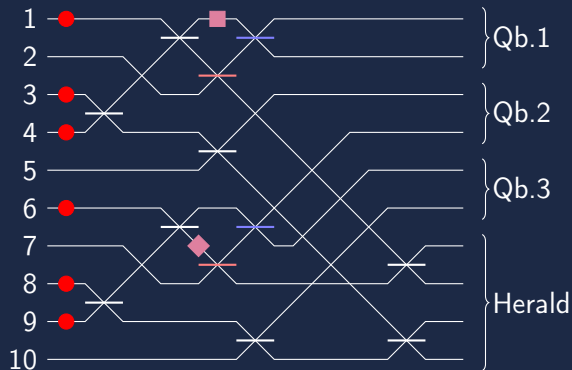


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- No deterministic CNOT in linear optics

From gates to resource states



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

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

From gates to resource states

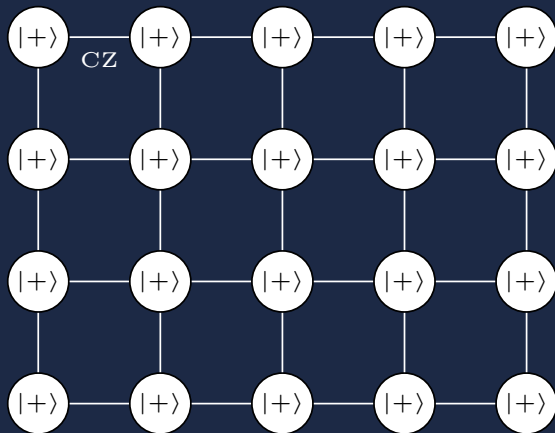


Figure: Graph state lattice $|G = (V, E)\rangle$

- 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

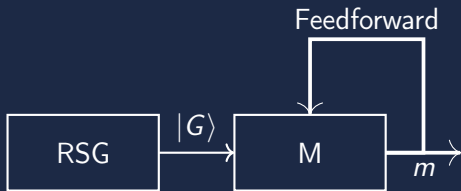


Figure: Measurement-based QC

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

From gates to resource states

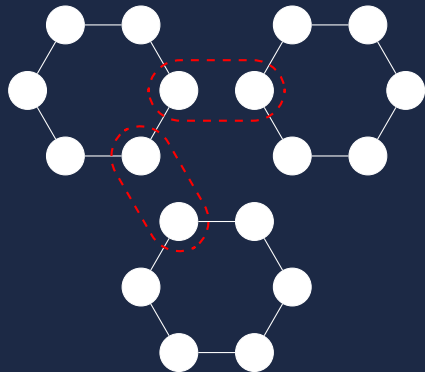


Figure: Fusion Based QC general ideas. (Fusion prob $1 - 1/2^n$)

- 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?

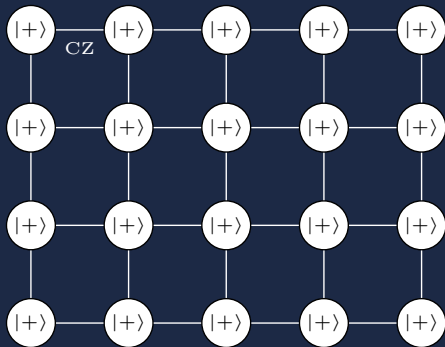


Figure: Graph state $|G\rangle$, with
 $G = (V, E)$

- 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?

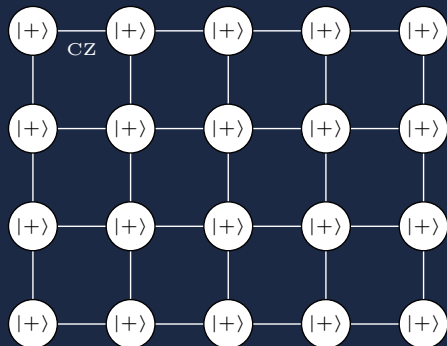


Figure: Graph state $|G\rangle$, with
 $G = (V, E)$

- 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

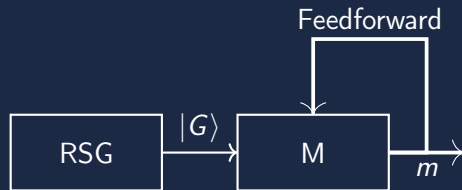


Figure: What is inside RSG???

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

Deterministic single-photon sources

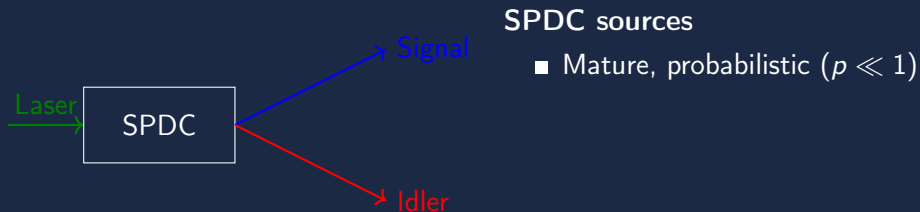


Figure: SPDC source (heralded)

Deterministic single-photon sources

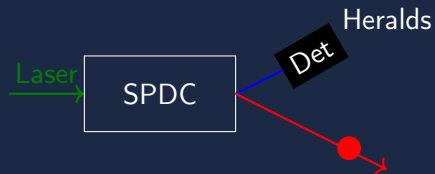
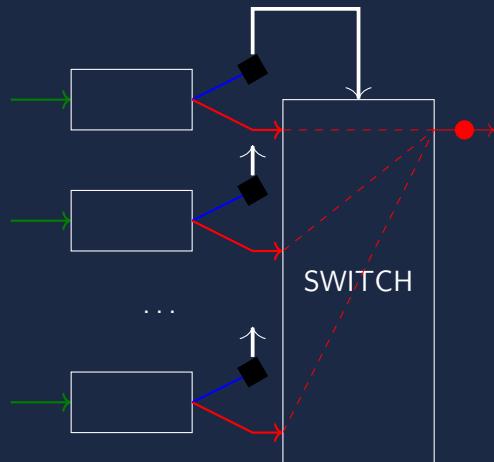


Figure: SPDC source (heralded)

SPDC sources

- Mature, probabilistic ($p \ll 1$)
- Heralded: detection of idler $\rightarrow$ signal photon

Deterministic single-photon sources

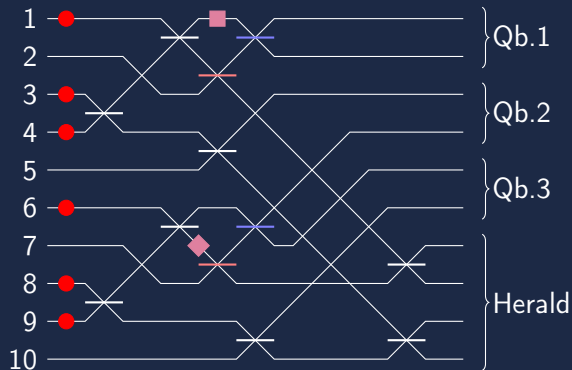


SPDC sources

- 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

Figure: Multiplexed SPDC sources

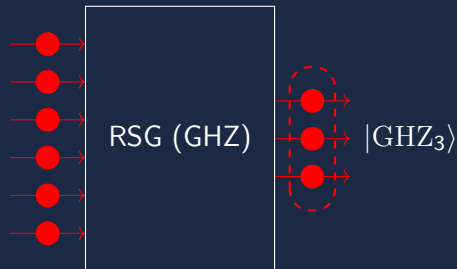
(Near-)Deterministic entanglement with photons



Each red circle requires multiplexed sources

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

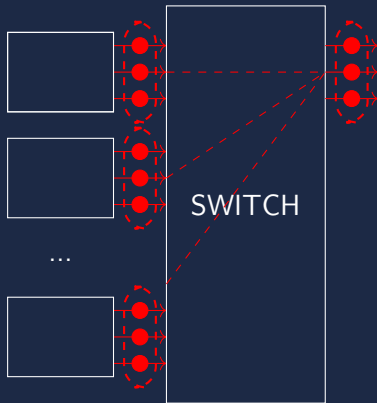
(Near-)Deterministic entanglement with photons



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
- Even more multiplexing
- Daunting resource overhead

Ways around:

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

Quantum Emitters

Deterministic photon sources

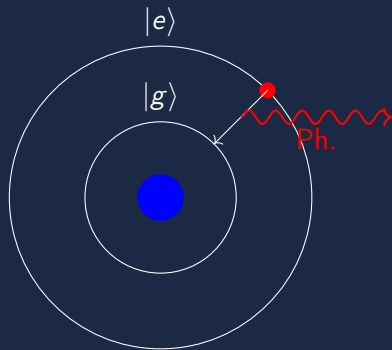


Figure: Scheme of the energy levels of an atom

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

Deterministic photon sources

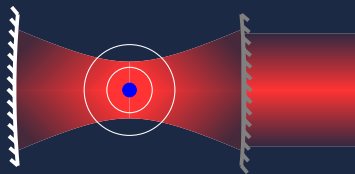


Figure: Atom embedded in an optical cavity. Directional emission

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Deterministic photon sources

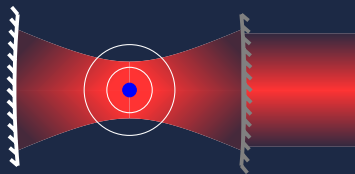


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Deterministic photon sources

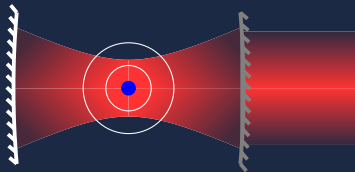
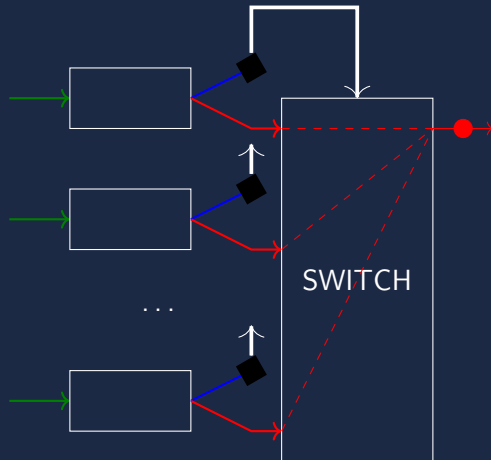


Figure: Atom embedded in an optical cavity. Directional emission

Replace



Deterministic photon sources

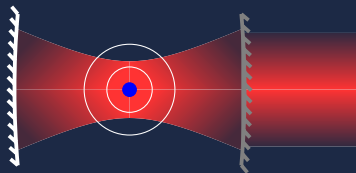
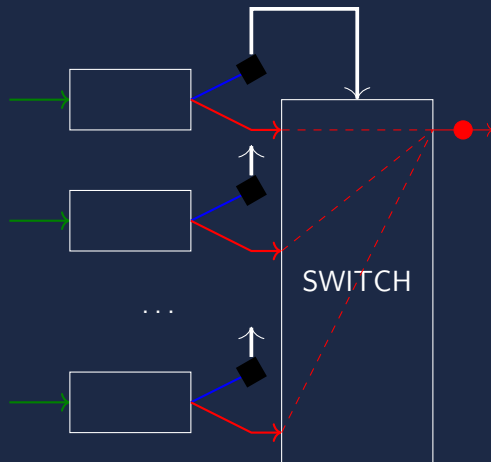


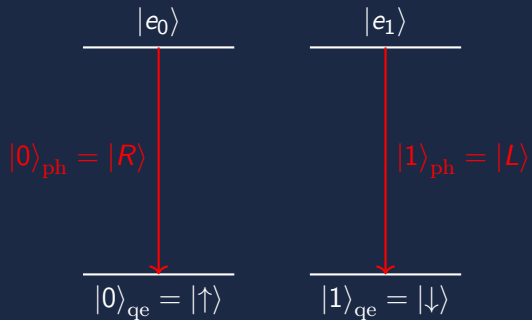
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Replace

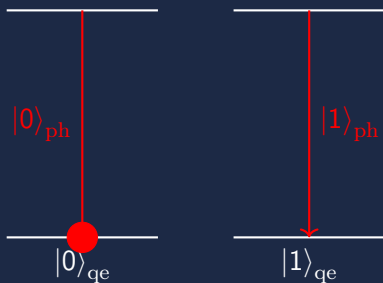


Can we do more?

Source of entangled photons



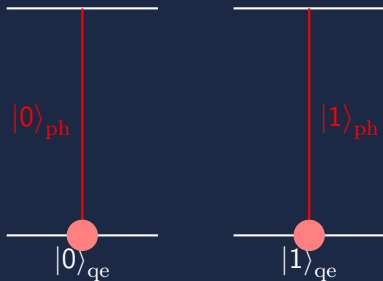
Source of entangled photons



Initialize:

$$|0\rangle_{\text{qe}}$$

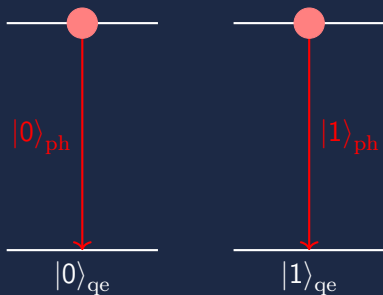
Source of entangled photons



Quantum superposition:

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

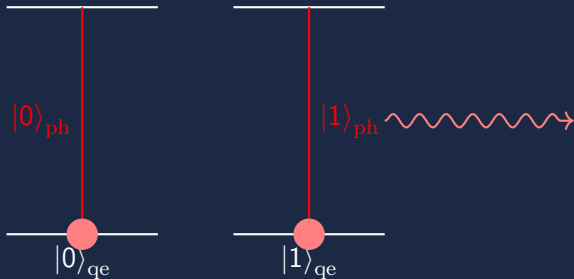
Source of entangled photons



Excite:

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

Source of entangled photons



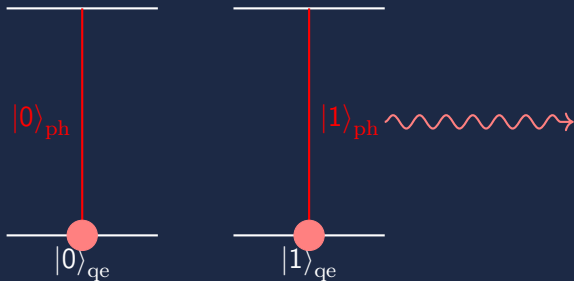
Photon emission (entanglement):

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

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

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

Source of entangled photons



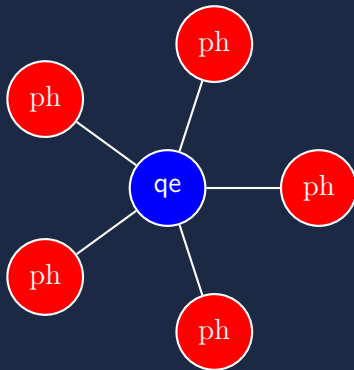
Repeat n times:

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

Deterministic source of GHZ states

Source of entangled photons

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



Up to H on photons

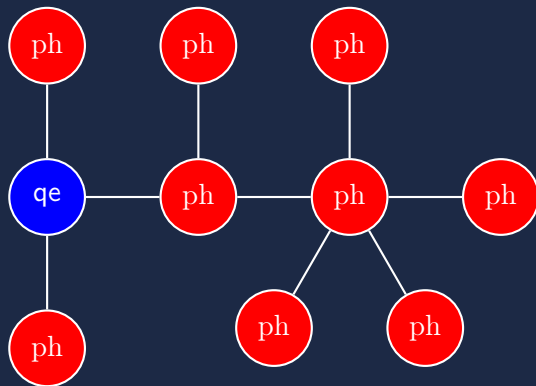
Source of entangled photons

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



Source of entangled photons

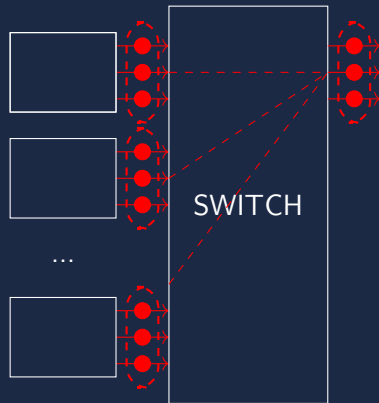
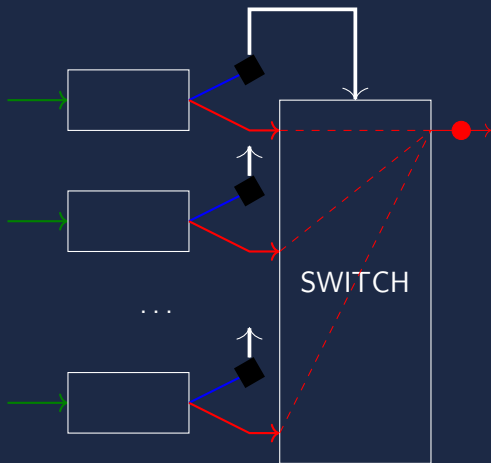
Caterpillar graph states



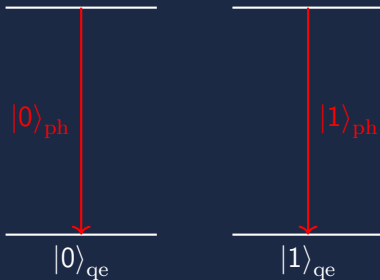
Most general graph that can be produced by a single quantum emitter ¹

¹B. Li et al., NPJ QI (2023)

Replacing complex linear-optics by advanced sources



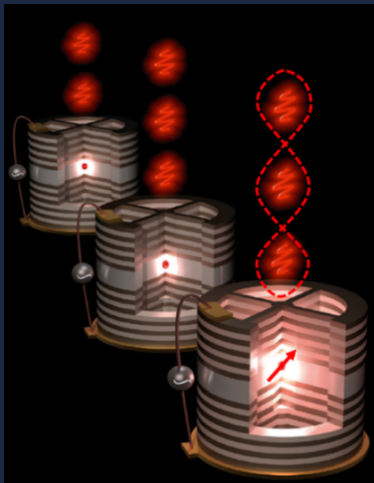
Replacing complex linear-optics by advanced sources



Replacing complex multiplexed linear-optics elements with advanced sources.

Experiments

The quantum emitter



Single-photon source

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

Figure: Quantum dot light source

The quantum emitter

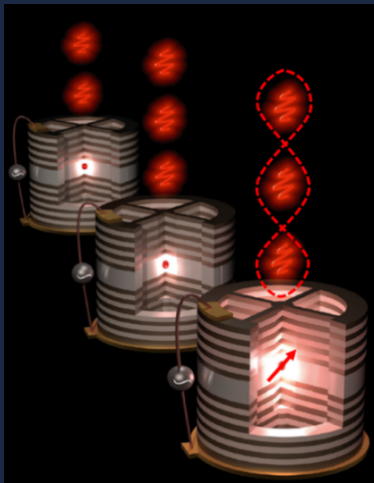


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Level structure

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

The quantum emitter

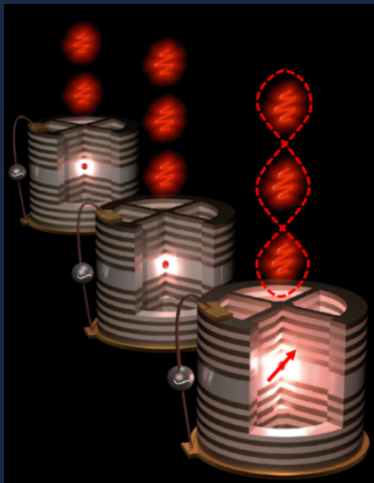


Figure: Quantum dot light source

Single-photon source

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- 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

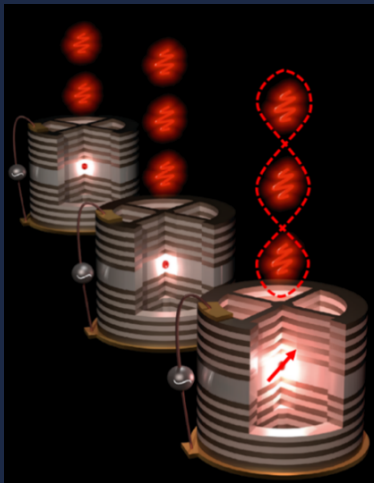


Figure: Quantum dot light source

- 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 caterpillar graphs ^e

^aA. Dousse et al., Phys. Rev. Lett., 101, 267404 (2008)

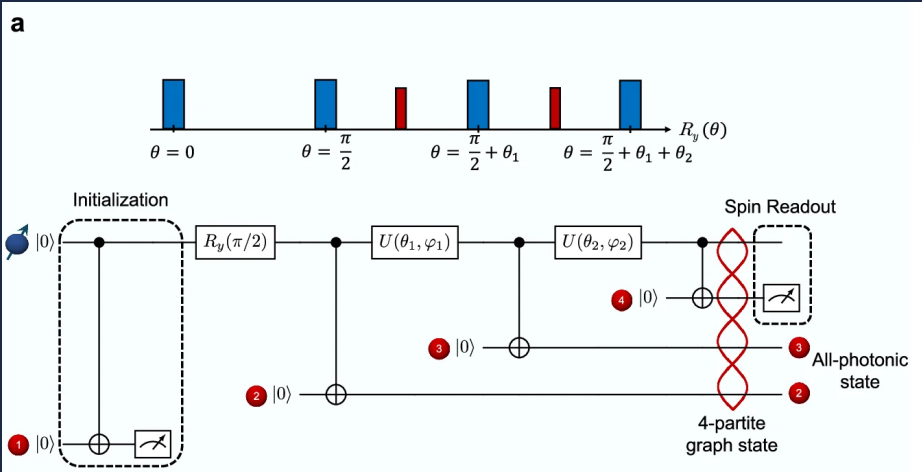
^bN. Somaschi et al., Nat. Photon., 10, 340 (2016)

^cP. Hilaire et al., Phys. Rev. B 102, 195402 (2020)

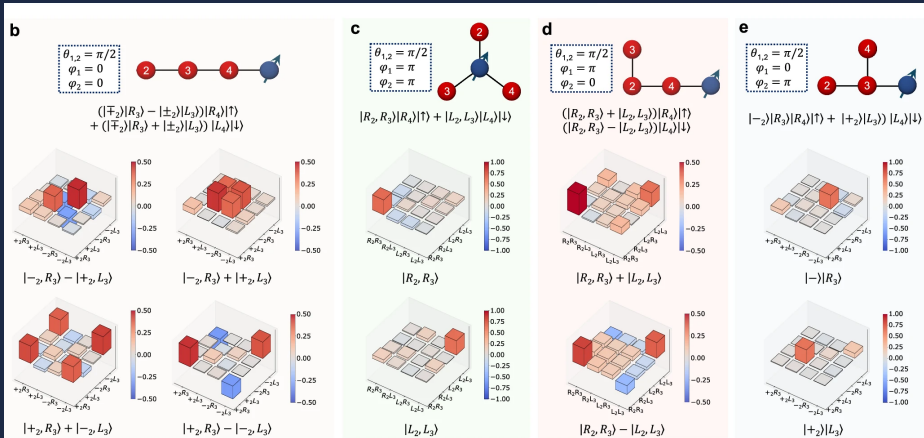
^dN. Coste et al., Nat. Photon., 17, 582 (2023)

^eH. Huet et al., Nat. Comm, 16, 4337 (2025)

Experiment



Experiment



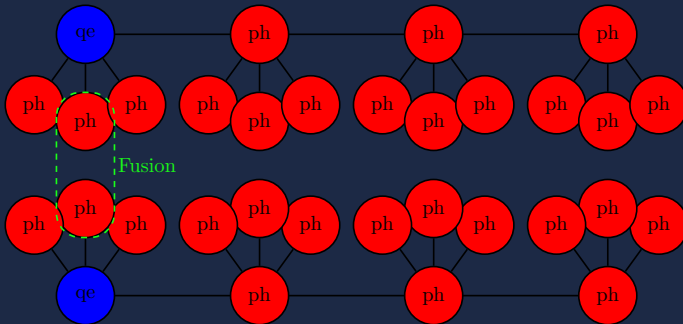
Fidelity $\approx 80\%$

What's next?

What's next?

Experimentally

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



Fusion Gates

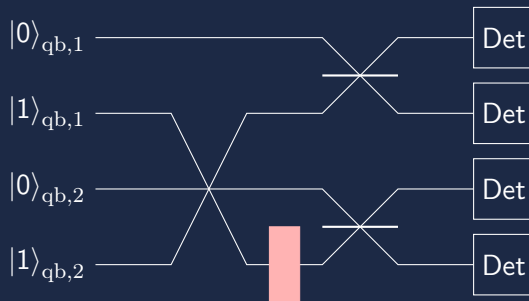


Figure: Fusion gate (Bell measurement)

Succeeds with probability $1/2$.

Ancilla-assisted fusions

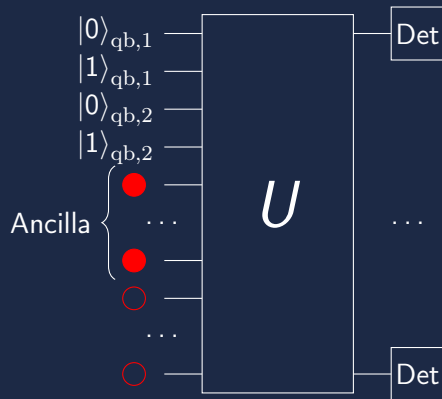
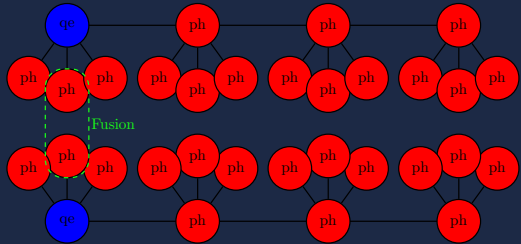
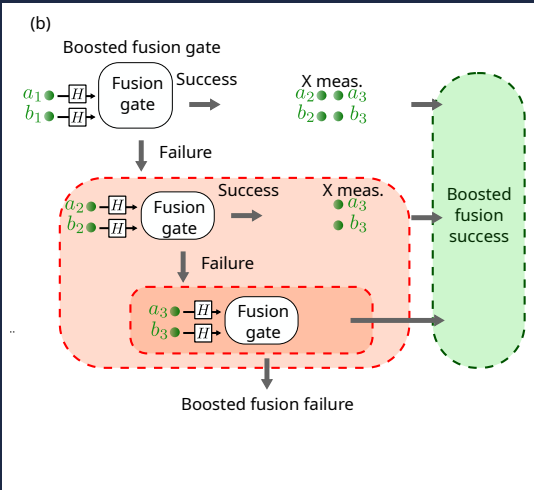


Figure: Ancilla-assisted fusion

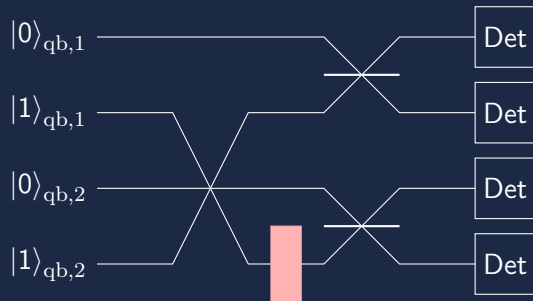
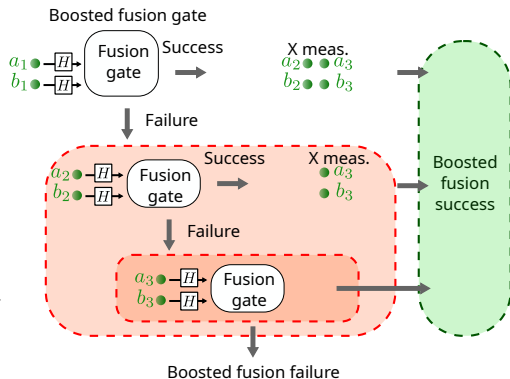
Success probability increased $1 - 1/2^n$ (for $2^n - 2$ ancilla photons)

Boosted Fusion Gates



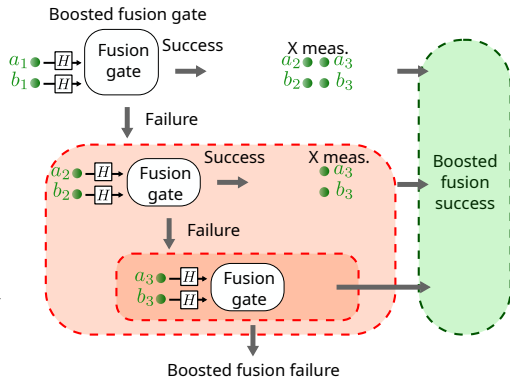
Boosted Fusion Gates

(b)



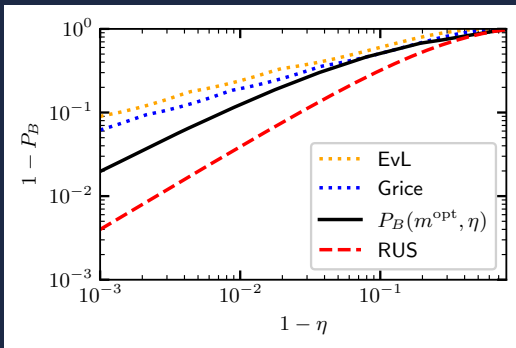
Boosted Fusion Gates

(b)



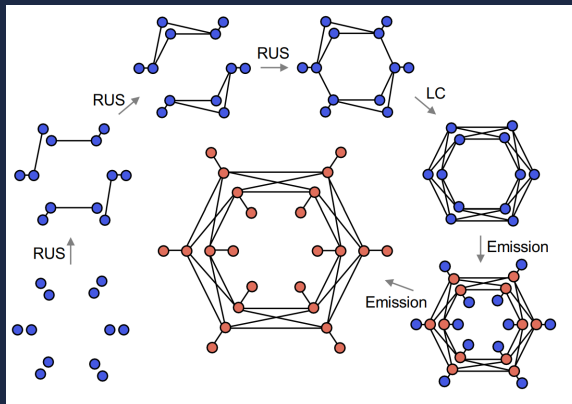
Larger success rate:

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



Recent result on resource optimisation ²

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



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

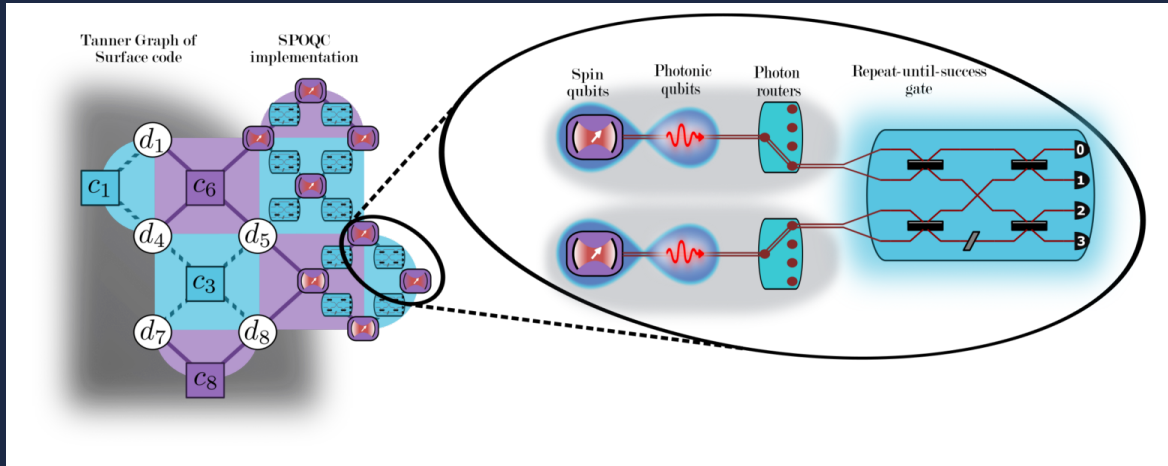
Recent result on resource optimisation ²

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%

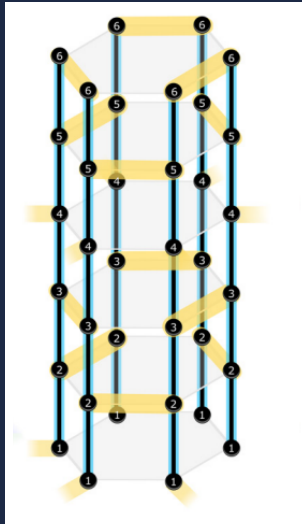
²S. Wein et al., ArXiv 2412.08611 (2024)

FTQC architectures: Spin-Optical Quantum Computing³



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

FTQC architectures: FBQC with spin-entangled graph states ⁴



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

- 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