Trapped Ions: Quantum Networks

MATTEO FADEL & ANNA HAMBITZER

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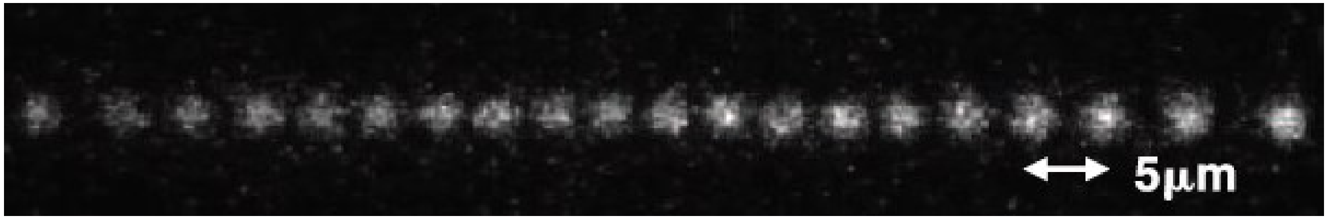
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Why to build a network?

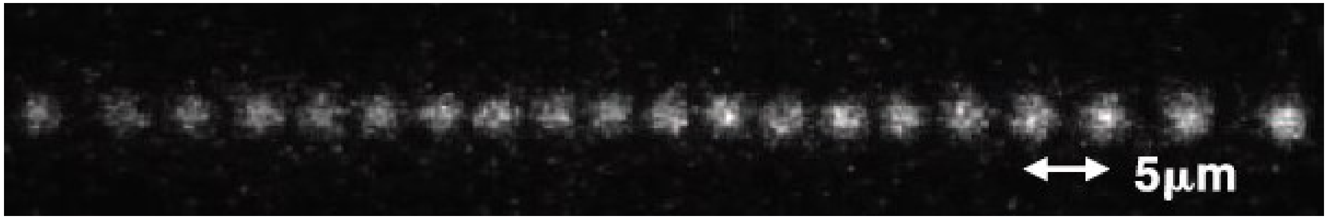


String of ions ⟶ Quantum Information Processor!

Significant LIMIT :
Number of ions (qubits) that can be trapped within the same potential.

Kimble The quantum internet

Why to build a network?

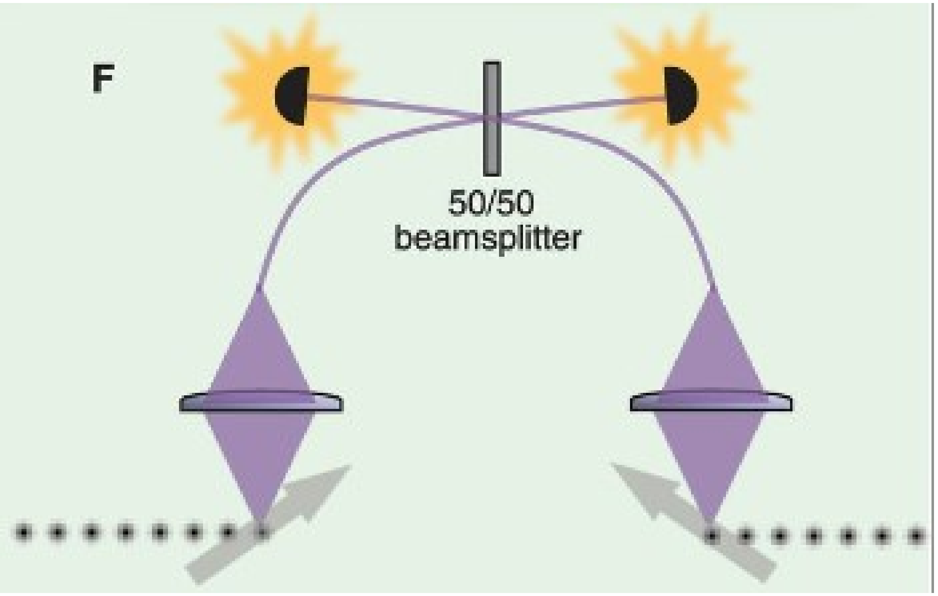


String of ions ⟶ Quantum Information Processor!

Significant LIMIT :
Number of ions (qubits) that can be trapped within the same potential.

Possible solution for scaling:

"connect" strings of ions together, using a (quantum) communication channel



Kimble The quantum internet

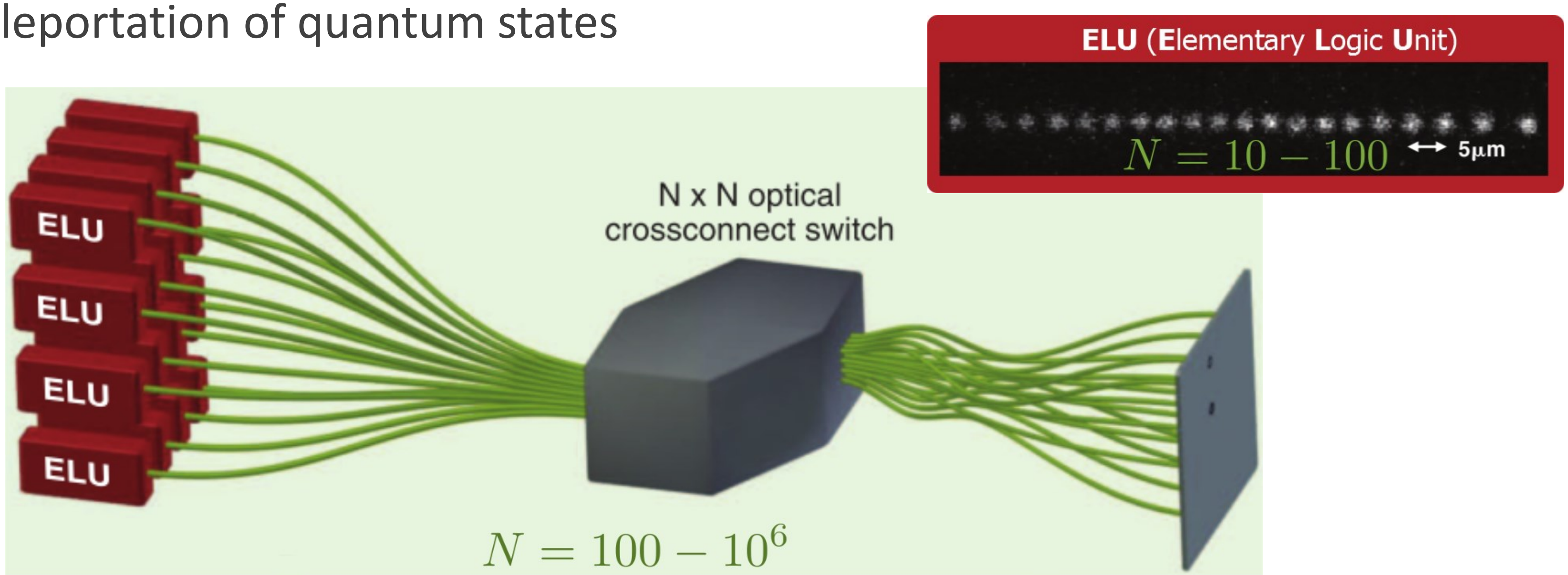
Network architectures

Why **quantum** channels?

- Preserve state superposition

  => $2 \times \text{nodes}$ classical states vs. 2^{nodes} Quantum states

- Teleportation of quantum states



How to create a quantum channel? $\longrightarrow$ use **entanglement**

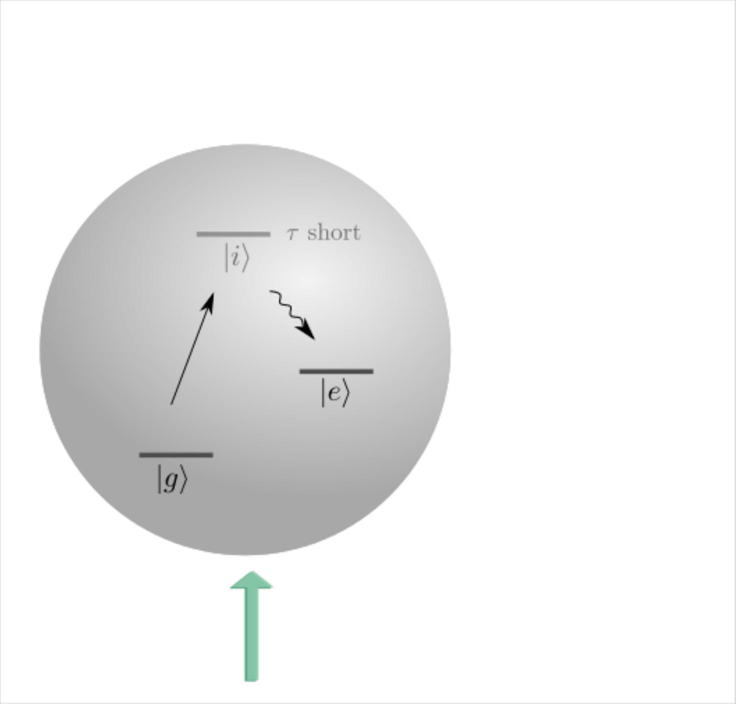
The Future of Quantum Information Processing. *Science*, *339* (2013).

Outline

- Creation of atom-atom entanglement
- Experimental realizations
- Perspectives & Discussion

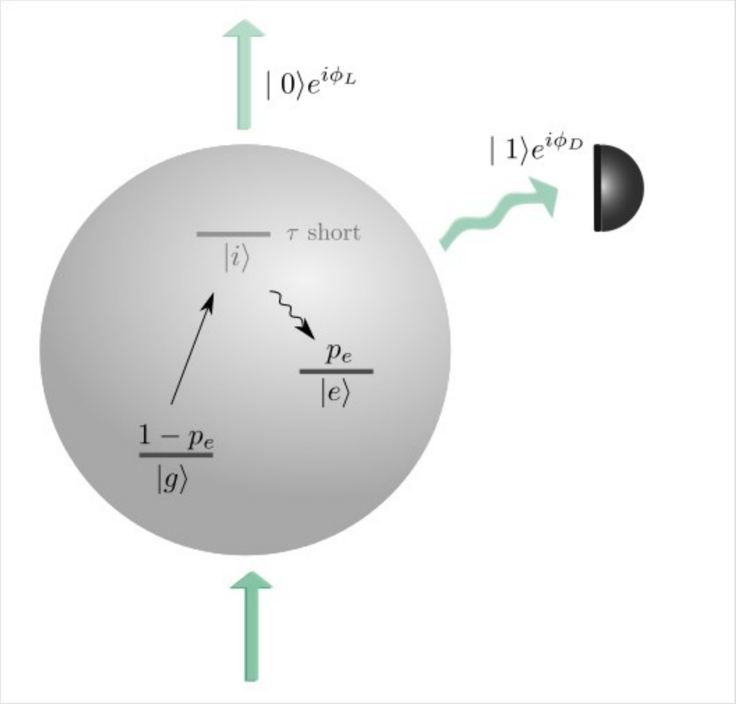
Creation of atom-atom entanglement

1 photon - 1 atom entanglement



- An atom with a **short lived upper state** is excited by a laser
- Spontaneous decay can lead to the final state $|e\rangle$

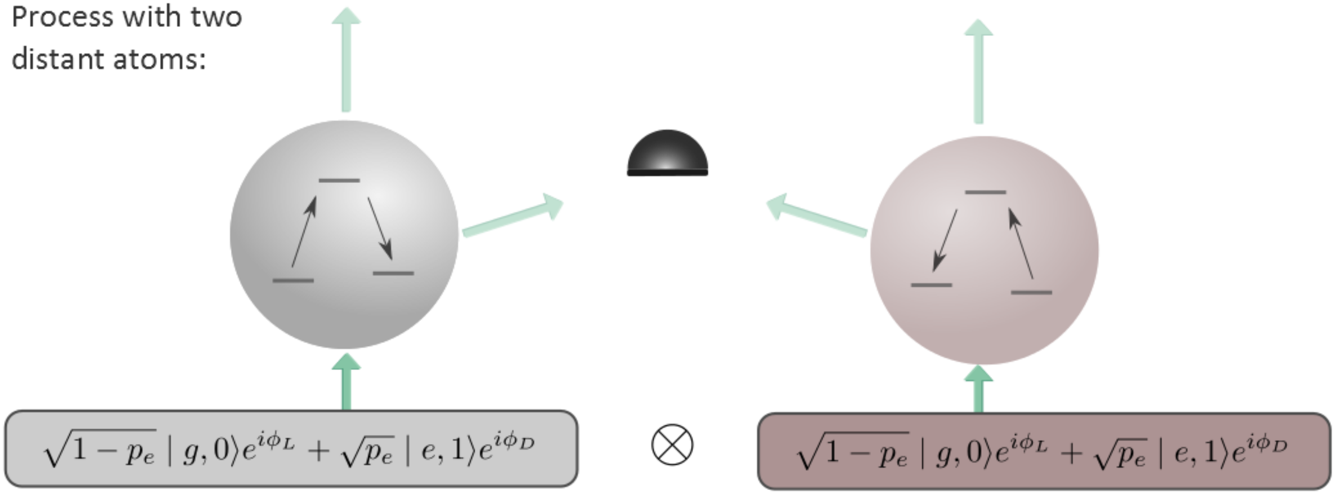
1 photon - 1 atom entanglement



- An atom with a **short lived upper state** is excited by a laser
- Spontaneous decay can lead to the final state $|e\rangle$
- The state of the atom and the photon becomes **entangled**

$$\sqrt{1-p_e}\,|\,g,0\rangle e^{i\phi_L}+\sqrt{p_e}\,|\,e,1\rangle e^{i\phi_D}$$

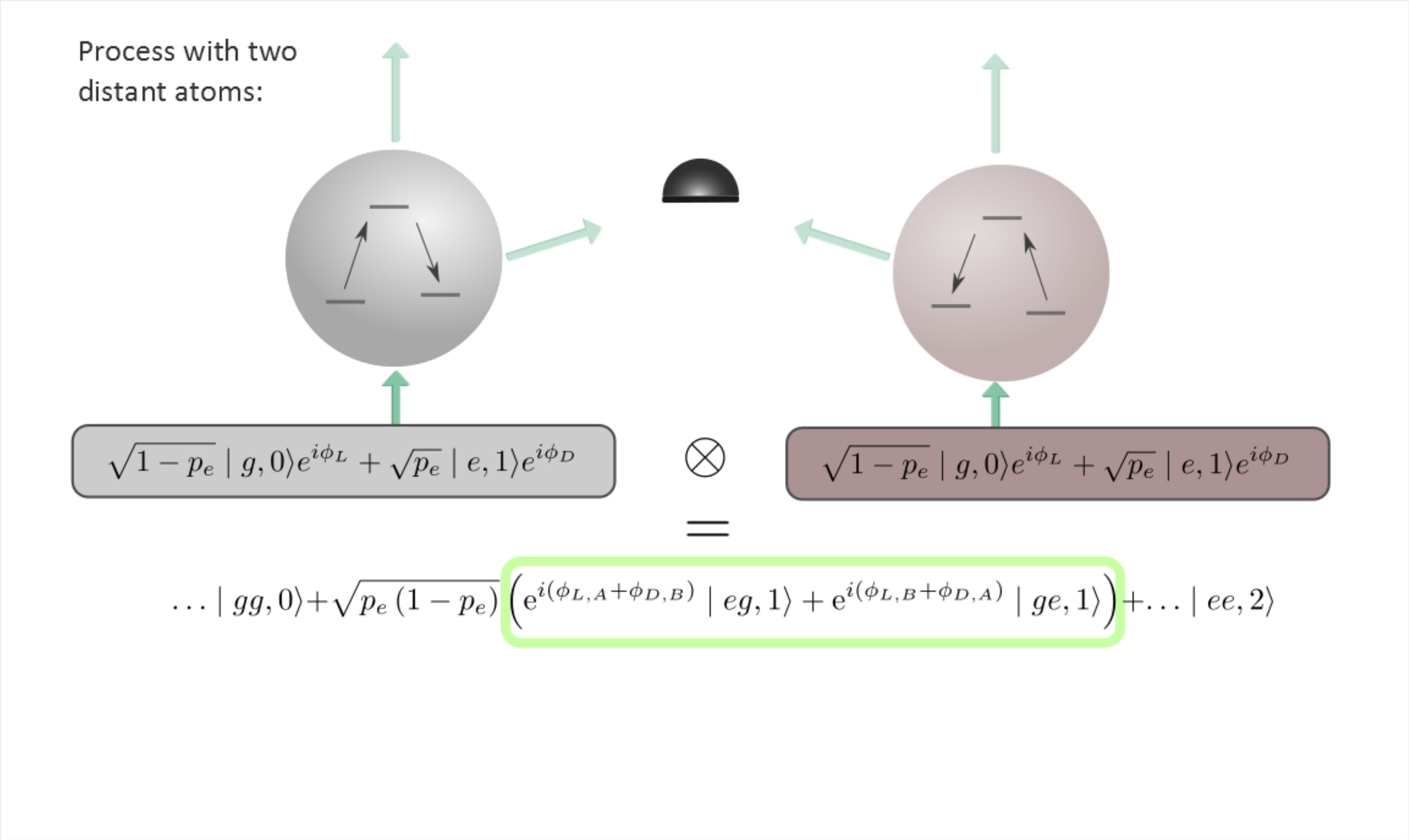
Atom – atom entanglement



Process with two distant atoms:

$$\sqrt{1-p_e}\,|\,g,0\rangle e^{i\phi_L} + \sqrt{p_e}\,|\,e,1\rangle e^{i\phi_D} \otimes \sqrt{1-p_e}\,|\,g,0\rangle e^{i\phi_L} + \sqrt{p_e}\,|\,e,1\rangle e^{i\phi_D}$$

Atom – atom entanglement



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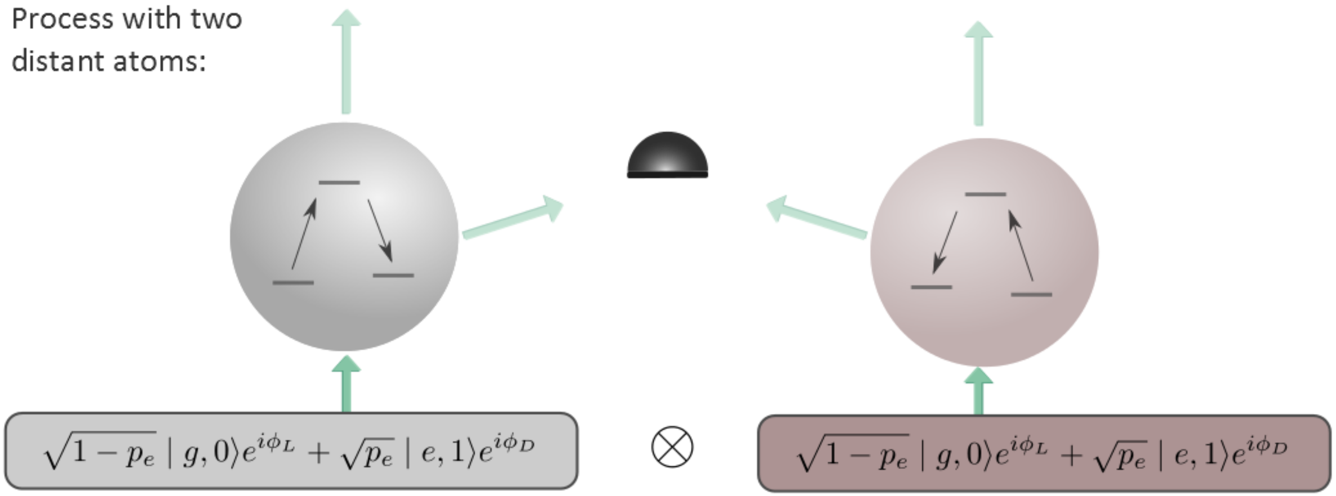
$$=$$

$$\ldots\,|\,gg,0\rangle+\sqrt{p_e\,(1-p_e)}\boxed{\left(\mathrm{e}^{i(\phi_{L,A}+\phi_{D,B})}\,|\,eg,1\rangle+\mathrm{e}^{i(\phi_{L,B}+\phi_{D,A})}\,|\,ge,1\rangle\right)}+\ldots\,|\,ee,2\rangle$$

Atom – atom entanglement



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1 photon detection **heralds** a (potential) **entangled atom state**

$$|\,\Psi^{\phi}\rangle = \frac{1}{\sqrt{2}}\left(|\,eg\rangle + e^{i\phi}\,|\,ge\rangle\right)$$

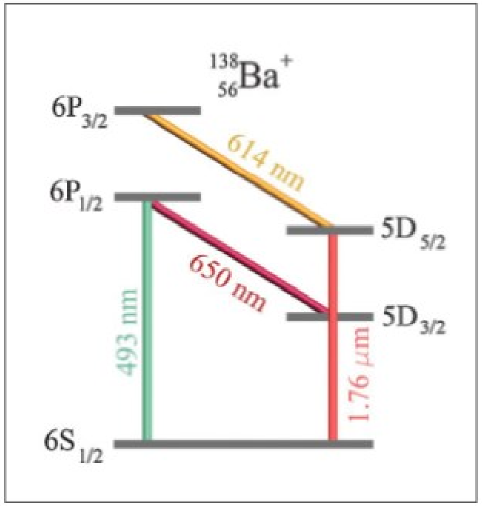
herald = ‘announce’

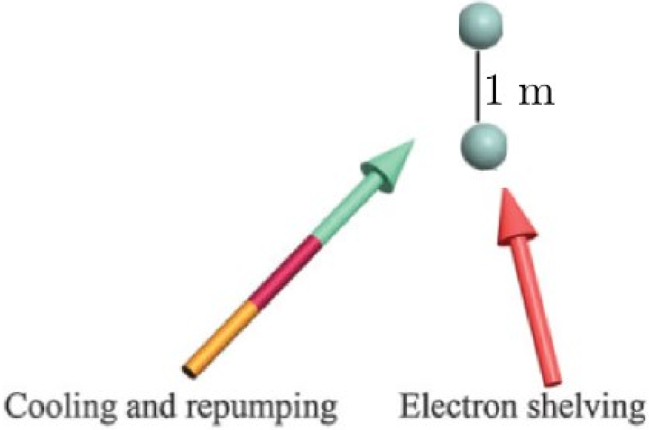
Experimental realization

1 photon heralding event

Experimental realization I

- Two **distant** barium atoms in a linear Paul trap
- Application of a **magnetic field** defines
  - Quantization axis
  - Qubit states





Figures adapted from [4]

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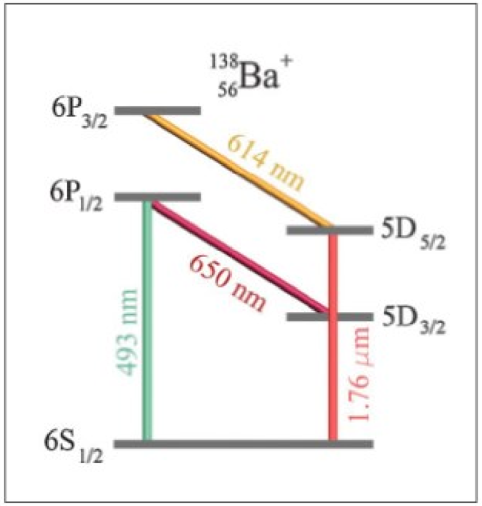
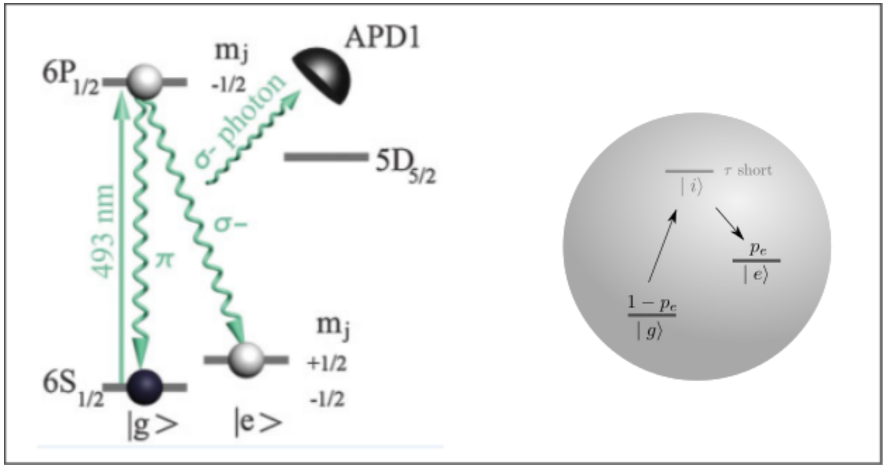
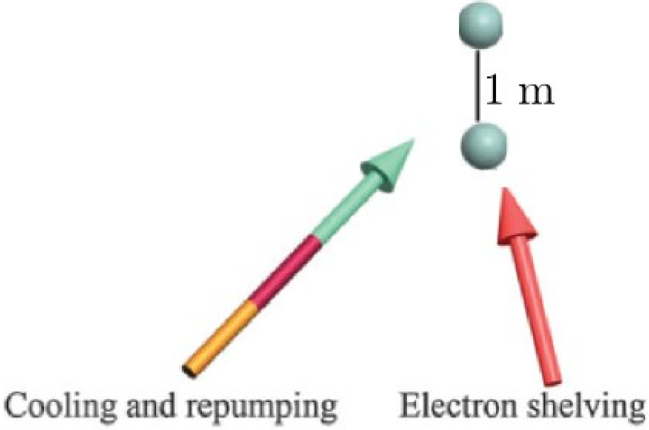






Figures adapted from [4]

Experimental realization I

The emitted photons must be **indistinguishable** in all degrees of freedom:

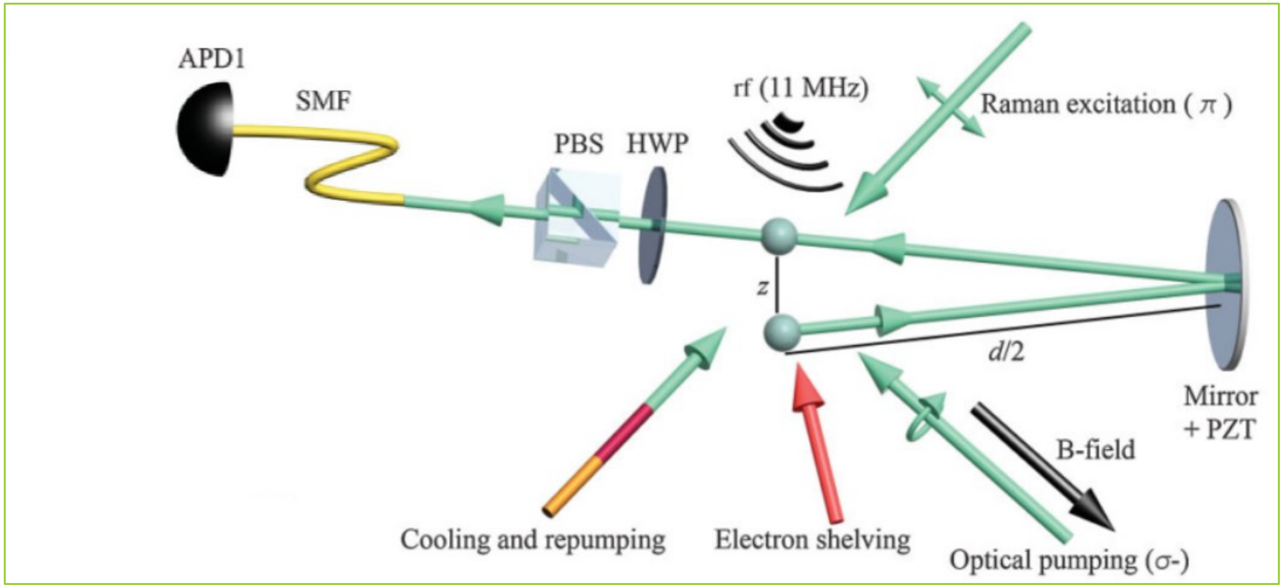
$$\ldots|gg,0\rangle+\sqrt{p_e\,(1-p_e)}\,\boxed{\left(e^{i(\phi_{L,A}+\phi_{D,B})}\,|eg,1\rangle+e^{i(\phi_{L,B}+\phi_{D,A})}\,|ge,1\rangle\right)}+\ldots|ee,2\rangle$$

detect photons without which way information

$$\boxed{|\Psi^{\phi}\rangle=\frac{1}{\sqrt{2}}\left(|eg\rangle+e^{i\phi}\,|ge\rangle\right)}$$

Atom: photon recoil

Photon: arrival time



Figures adapted from [4]

Entanglement fidelity

- Preparation of a Bell state by setting the phase

$$|\Psi^{\phi}\rangle = \frac{1}{\sqrt{2}}\left(|eg\rangle + e^{i\phi}|ge\rangle\right) \xrightarrow[\text{ion distance \& mirror position}]{\phi=0} |\Psi^{+}\rangle = \frac{1}{\sqrt{2}}\left(|eg\rangle + |ge\rangle\right)$$

- How high is the **fidelity** of the entanglement creation?

$$F = \langle\Psi^{+}|\hat{\rho}|\Psi^{+}\rangle \qquad |\Psi^{+}\rangle = \frac{1}{\sqrt{2}}\left(|eg\rangle + |ge\rangle\right)$$

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$$\boxed{F = \langle\Psi^{+}|\hat{\rho}|\Psi^{+}\rangle = \frac{1}{2}[\underbrace{\rho_{ge} + \rho_{eg}}_{\text{one excitation}} + \underbrace{2\mathrm{Re}(\rho_{eg,ge})]}_{\text{coherence}}}$$

Entanglement fidelity

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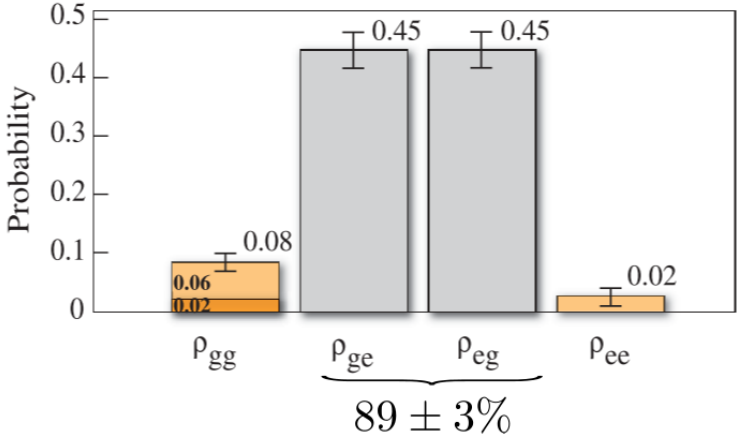
- How well does the 1 photon detection herald that **one atom** is excited?



Result from [4]

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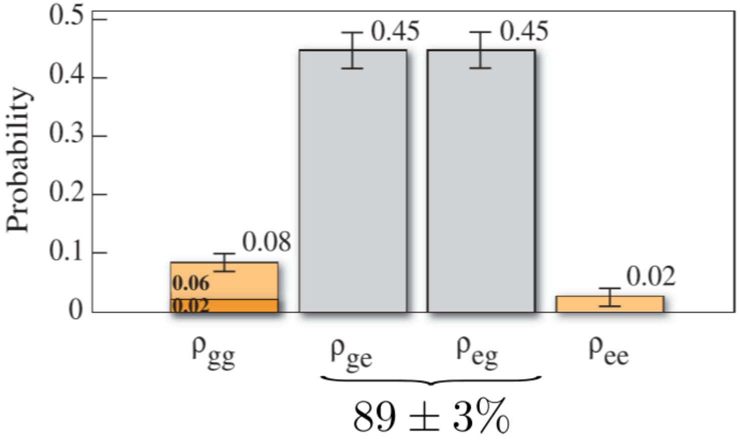
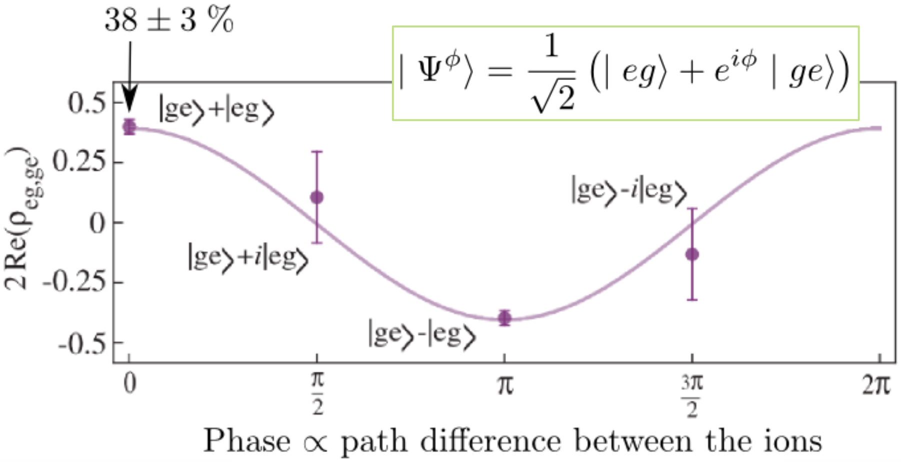


- ○ The coherence can be measured by application of global rf-pulses:



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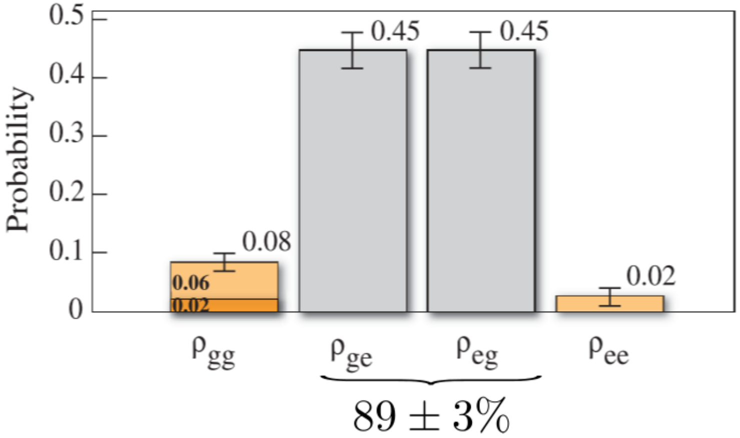

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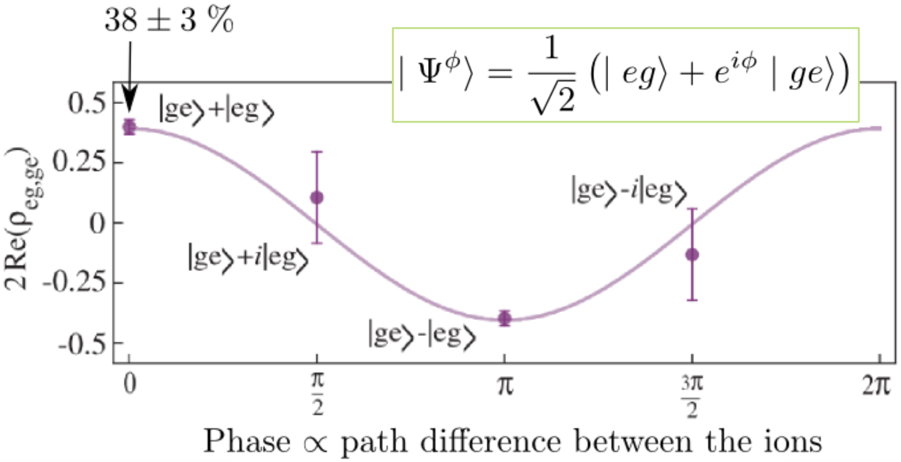


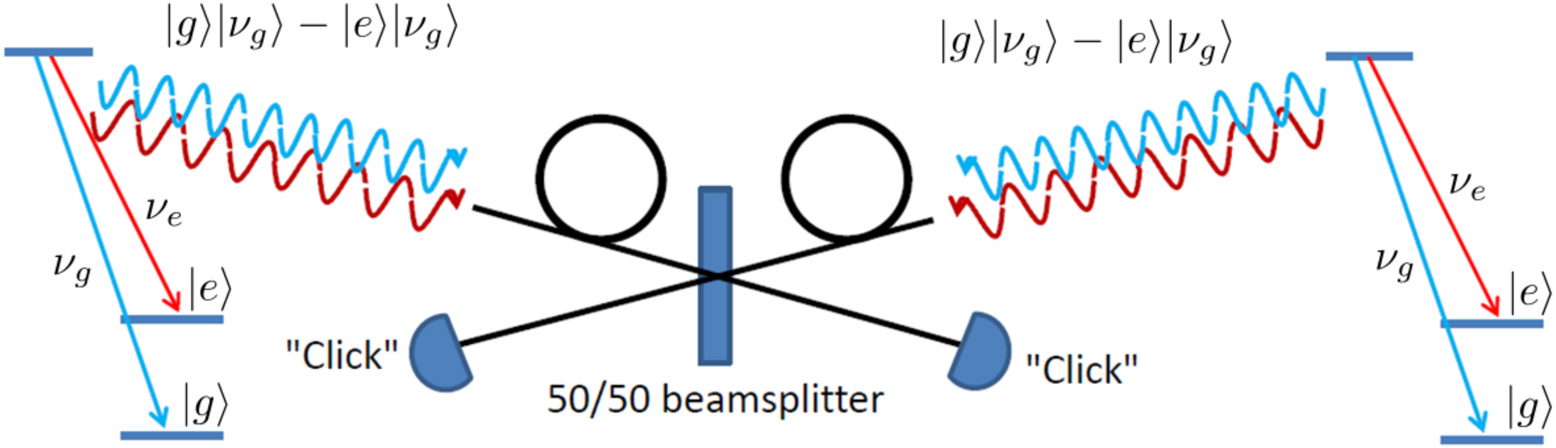
$$\boxed{F = \frac{1}{2}[89\ \% + 38\ \%] = 64\%}$$

Result from [4]

Experimental realization

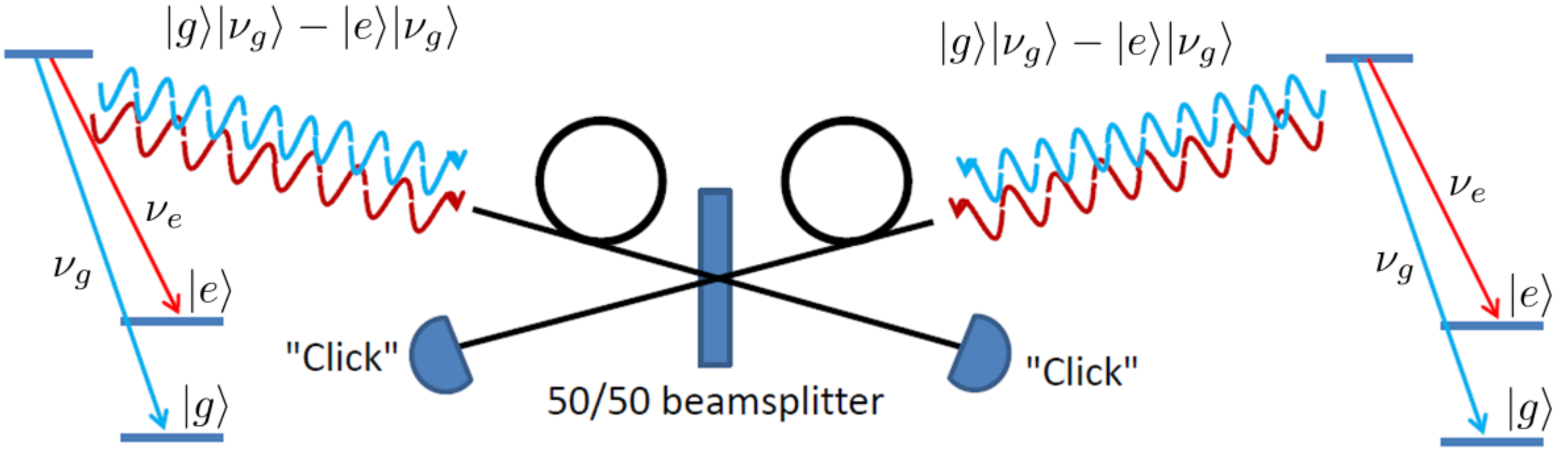
2 photons heralding event

Two-photons setup



$$(|g,\nu_g\rangle_\mathrm{A} - |e,\nu_e\rangle_\mathrm{A}) \otimes (|g,\nu_g\rangle_\mathrm{B} - |e,\nu_e\rangle_\mathrm{B}) =$$

Two-photons setup



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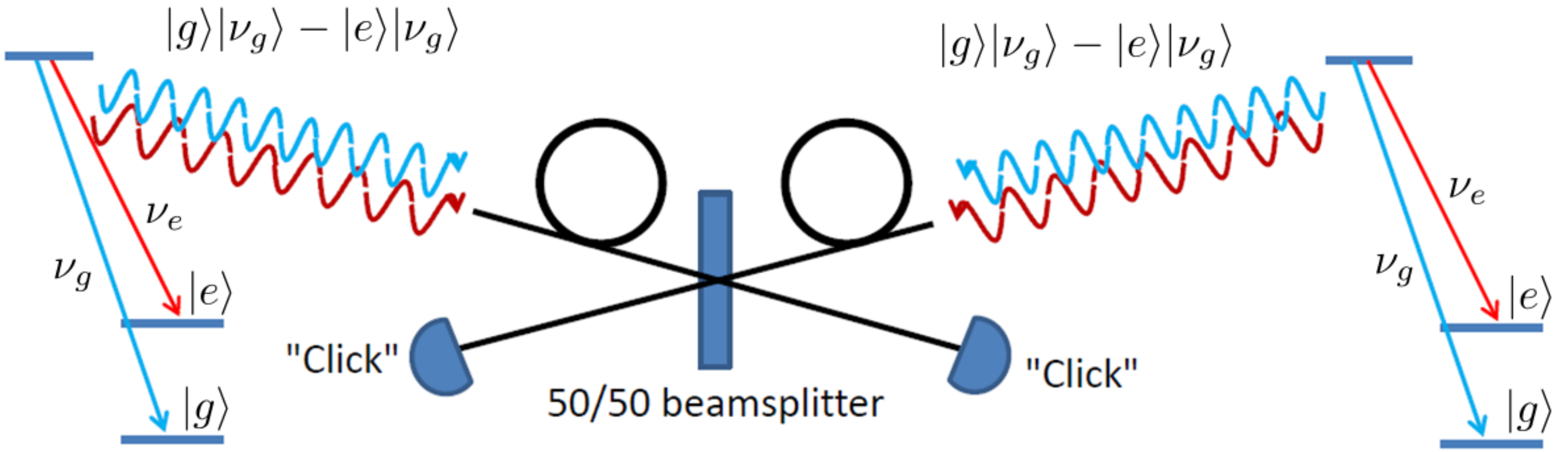
$$= (\, |g,\nu_g\rangle_\mathrm{A}|g,\nu_g\rangle_\mathrm{B} + |e,\nu_e\rangle_\mathrm{A}|e,\nu_e\rangle_\mathrm{B} - |g,\nu_g\rangle_\mathrm{A}|e,\nu_e\rangle_\mathrm{B} - |e,\nu_e\rangle_\mathrm{A}|g,\nu_g\rangle_\mathrm{B} \,)$$

Two-photons setup



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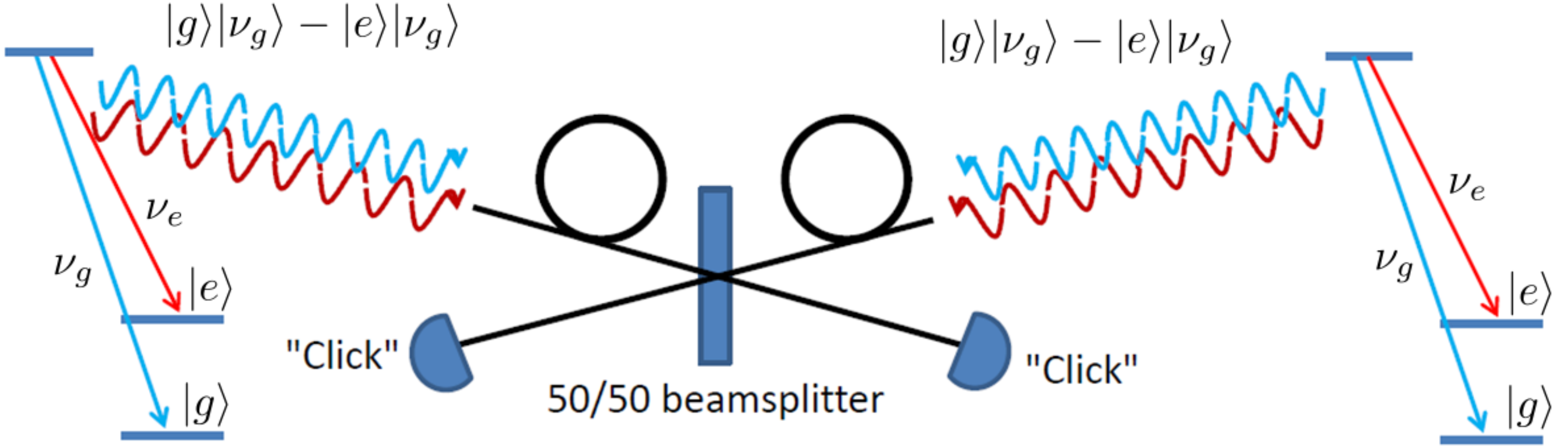
Simultaneous detection of two photons (with the same polarization) after the beam splitter only if they come with different frequencies and if their wavefunction is **antisymmetric**.

Two-photons setup



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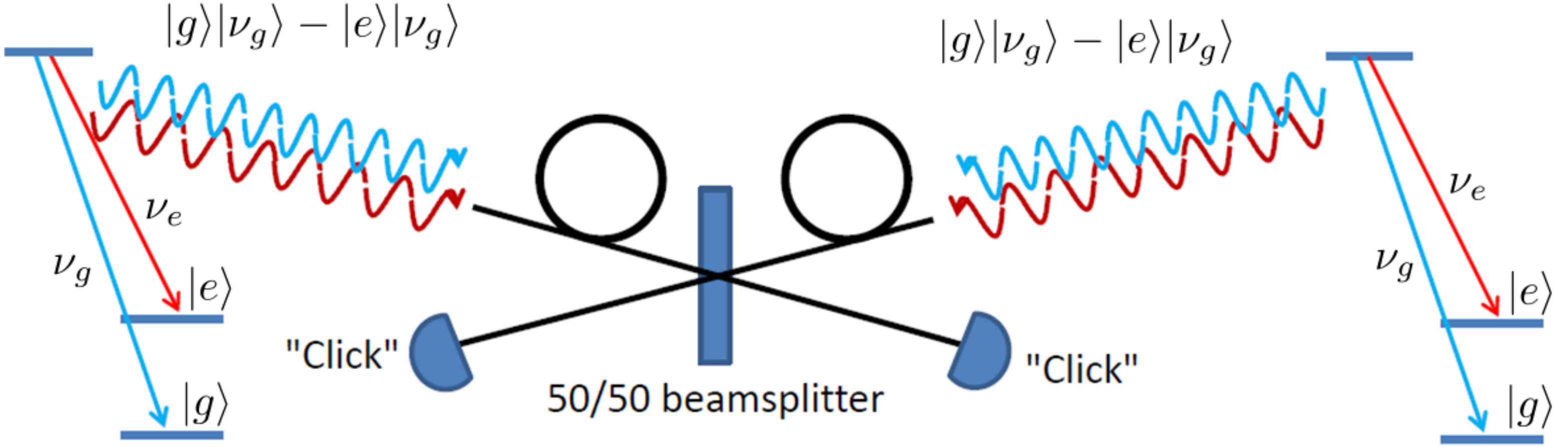

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$$= (\ldots - \boxed{(|ge\rangle - |eg\rangle)(|\nu_g\nu_e\rangle - |\nu_e\nu_g\rangle)} - (|ge\rangle + |eg\rangle)(|\nu_g\nu_e\rangle + |\nu_e\nu_g\rangle) \ )$$

After the measurement: $(|g_{\mathrm{A}}e_{\mathrm{B}}\rangle - |e_{\mathrm{A}}g_{\mathrm{B}}\rangle)$ Entangled state!

Comparison

	Rainer Blatt's group 2013 doi:10.1103/PhysRevLett.110.083603		**C. Monroe's group 2007** doi:10.1038/nature06118
Heralding event	**Single photon detection**		**Two photons coincidence**
Fidelity	$64 \pm 2\ \%$	$\longleftrightarrow$	$63 \pm 3\ \%$
Success probability	1.1×10^{-4}	$\xleftarrow{10^5}$	3.6×10^{-9}
Entanglement events (in 8.5 minutes)	119	$\xleftarrow{10^2}$	1

Discussion

Fidelity

$$64 \pm 2\,\% \quad \longleftrightarrow \quad 63 \pm 3\,\%$$

- ➢ The fidelity is not high, main limitation is the residual motion >> **cooling**

Entanglement events (in 8.5 minutes)

$$119 \quad \xleftarrow{10^2} \quad 1$$

- ➢ One entanglement event in 5 s vs coherence time of ~ 10 s

Success probability

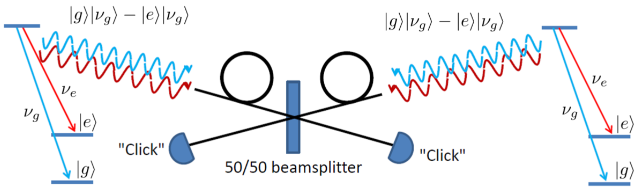
$$1.1 \times 10^{-4} \quad \xleftarrow{10^5} \quad 3.6 \times 10^{-9}$$

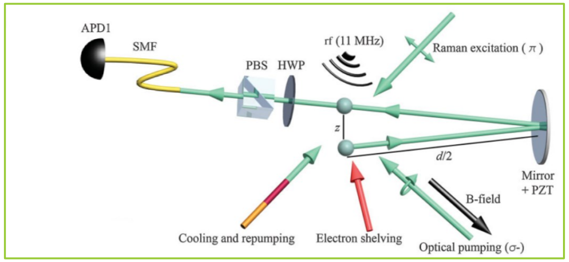
- ➢ Main limit for the success probability is the **efficiency for the detection** of a single Raman scattered photon

Summary

- Quantum networks are essential tools for scaling and quantum information transfer

- Entanglement between remote qubits (ions) needs to be **created and heralded**





Low probability of **simultaneous emission of two photons** with different frequencies corresponds to a lower entanglement rate

- **1 photon detection** heralds entanglement
- Rate increased by **x 100**
- Fidelity limited by the which way information from **residual motion**

Literature

[1] Special Issue (2013). *The Future of Quantum Information Processing*. Science, 339(March).

[2] Kimble, H. J. (2008). *The quantum internet*. Nature, 453(7198), 1023–30.

[3] Moehring, D. L. et al. (2007). *Entanglement of single-atom quantum bits at a distance.* Nature, 449(September). 6118

[4] He, G. et al. (2013). *Atom-Atom Entanglement by Single-Photon Detection. Physical Review Letters*, 083603(February), 1–5.

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