Quantum Simulation Using Photons

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Lecture I:
Quantum Photonics
Experimental Groups doing Quantum Computation & Simulation

- **Atoms (Harvard, MIT, MPQ, Hamburg,...)**:
  - single atoms in optical lattices
  - transition superfluid $\rightarrow$ Mott insulator

- **Trapped Ions (Innsbruck, NIST, JQI Maryland, Ulm...)**:
  - quantum magnets
  - Dirac’s Zitterbewegung
  - frustrated spin systems
  - open quantum systems

- **NMR (Rio, SaoPaulo, Waterloo, MIT, Hefei,...)**:
  - simulation of quantum dynamics
  - ground state simulation of few (2-3) qubits

- **Superconducting Circuits (ETH, Yale, Santa Barbara,...)**:
  - phase qudits for measuring Berry phase
  - gate operations

- **Single Photons (Queensland, Rome, Bristol, Vienna,...)**
  - simulation of $\text{H}_2$ potential (Nat.Chem 2, 106 (2009))
  - quantum random walks (PRL 104, 153602 (2010))
  - spin frustration
Architecture race for quantum computers

Quantum computers
A little bit, better

After decades languishing in the laboratory, quantum computers are attracting commercial interest

Jun 20th 2015 | From the print edition

• UK: 270 M£
• Netherlands: 135 M€
Why Photons?

- only **weak interaction** with environment (good coherence)

- **high-speed** (c), low-loss transmission (‘flying qubits’)

- good **single-qubit control** with standard optical components (waveplates, beamsplitters, mirrors,...)

- feasible **hardware requirements** (no vacuum etc.)

- disadvantage: **weak two-photon interactions**
  (requires non-linear medium -> two-qubit gates are hard)
Outlook of the Course

(1) Quantum Photonics Concepts and Technology

(2) Quantum Simulation

(3) Photonic Quantum Simulation Examples
   - Analog Quantum Simulator
   - Digital Quantum Simulator
   - Intermediate Quantum Computation

(4) Schemes based on superposition of gate orders
Basic Elements in Photonic Quantum Computing and Quantum Simulation
(1) Five Lectures on Optical Quantum Computing (P. Kok)

(2) Linear optical quantum computing with photonic qubits
Photonic Quantum Computer Units

Preparation

Manipulation

Detection

Quantum Photonics Resource Quantum Computing @ Uni Wien
How to encode information using photons

- **Polarization**
  
  $$|0\rangle = |H\rangle$$
  $$|1\rangle = |V\rangle$$

- **Spatial Location** – dual rail representation

  $$|0\rangle_z = |01\rangle$$
  $$|1\rangle_z = |10\rangle$$
- Qubit as elementary unit of (quantum) information
- Spans a 2d-Hilbert space

\[
\frac{|0\rangle + i|1\rangle}{\sqrt{2}}
\]

\[
\frac{|0\rangle - |1\rangle}{\sqrt{2}}
\]

\[
\frac{|H\rangle + i|V\rangle}{\sqrt{2}}
\]

\[
\frac{|H\rangle - |V\rangle}{\sqrt{2}}
\]
Feasible Manipulation of Polarization

Hadamard gate

\[ |H\rangle \rightarrow \frac{|H\rangle + |V\rangle}{\sqrt{2}} \]

22.5°

Arbitrary rotation gate

\[ |H\rangle \rightarrow \lambda_4 \lambda_2 \lambda_4 \alpha |H\rangle + \beta |V\rangle \]

PBS

\[ \alpha |0\rangle \]

Multi-photon Sources
Two (and Multi-Photon) Generation

- Spontaneous parametric down conversion of pump field (CW or pulsed) in $\chi(2)$-medium
- Proper mode selection leads to polarization entanglement due to indistinguishability

$$H \propto (a_A^\dagger(\omega_1, V)a_B^\dagger(\omega_2, H) - a_A^\dagger(\omega_2, H)a_B^\dagger(\omega_1, V))$$

$k_{\text{pump}} = k_{\text{photon1}} + k_{\text{photon2}}$

$w_{\text{pump}} = w_{\text{photon1}} + w_{\text{photon2}}$
Entanglement on the Screen
For achieving high-quality entanglement

Erase which path information (originating from bi-refringence):
Additional compensator crystals:

Flipping:
To:

maximally entangled state: $|\psi\rangle = \frac{1}{\sqrt{2}} \left( |H\rangle_1 |V\rangle_2 - e^{i\varphi} |V\rangle_1 |H\rangle_2 \right)$ \quad \varphi = 0, \pi
SPDC at the breadboard level
Sagnac interferometric configuration

**Benefits:** stability and high brightness

Pulse FHWM temporal width $\cong 2 ps$ (PPKTP crystal length of 30mm)

High-repetition rate pump pulses

Passive temporal multiplexing scheme:
- increasing the pump laser repetition rate
- thus: reducing the energy of each pulse from the pump beam

\[ C_{acc} = \frac{N_1 N_2}{f} \quad \text{with } N_i \quad \text{single photon rate for detector} \quad i = 1, 2 \]

Doubling the pump laser repetition rate \( f \):

Increasing 8 times \( f \):

Broome, Almeida, White, Optics Express 19, 022698 (2011)
- Probabilistic photon pair emission $p \sim 0,02$
- Probability that $n$ sources emit $p^n$
Probabilistic Single-Photon Sources

- Probabilistic photon pair emission $p \sim 0.02$
- Probability that $n$ sources emit $p^n$

**Experimental ten-photon entanglement**


(Submitted on 27 May 2016)

Quantum entanglement among multiple spatially separated particles is of fundamental interest, and can serve as central resources for studies in quantum nonlocality, quantum-to-classical transition, quantum error correction, and quantum simulation. The ability of generating an increasing number of entangled particles is an important benchmark for quantum information processing. The largest entangled states were previously created with fourteen trapped ions, eight photons, and five superconducting qubits. Here, based on spontaneous parametric down-converted two-photon entanglement source with simultaneously a high brightness of $\sim 12 \text{ MHz/}W$, a collection efficiency of
Probabilistic Single-Photon Sources

- Probabilistic photon pair emission $p \sim 0.02$
- Probability that $n$ sources emit $p^n$

<table>
<thead>
<tr>
<th>$N$-photon GHZ state</th>
<th>2 (*)</th>
<th>4 (*)</th>
<th>6 (*)</th>
<th>8 (*)</th>
<th>10 (*)</th>
<th>10 (**)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fidelity</td>
<td>0.9720(1)</td>
<td>0.833(4)</td>
<td>0.710(16)</td>
<td>0.644(22)</td>
<td>0.573(23)</td>
<td>0.429(21)</td>
</tr>
<tr>
<td>Distillable entanglement, $\sigma$</td>
<td>5215</td>
<td>122.3</td>
<td>20.8</td>
<td>17.7</td>
<td>15.2</td>
<td>7.2</td>
</tr>
<tr>
<td>Genuine entanglement, $\sigma$</td>
<td>4334</td>
<td>84.6</td>
<td>13.3</td>
<td>6.5</td>
<td>3.1</td>
<td>-3.4</td>
</tr>
<tr>
<td>Count rate (Hz)</td>
<td>1000000</td>
<td>60000</td>
<td>39</td>
<td>0.2</td>
<td>0.0011</td>
<td>0.0031</td>
</tr>
</tbody>
</table>

* under a laser pump power of 0.57 W.  ** under a laser pump power of 0.7 W.
Approaches for non-exponential scaling of photon generation:
(1) Quantum Repeater (atoms, memory etc) → e.g. DLCZ scheme
(2) On-demand single-photon sources (dots, cavity-QED)
(3) Multiplexing of probabilistic sources (no atoms required)

Temporal multiplexing: → 6 times enhancement achieved
Spatial multiplexing: → 2-4 times enhancement achieved
Single-photon Detectors
Technology for Single-Photon Detection

- Probabilistic emission of down-converted photons

\[ \text{Coinc} \propto \eta^N \]

- New quantum technologies open path for (probabilistic) multi-photon experiments

<table>
<thead>
<tr>
<th>$N$ photon pair number</th>
<th>generated events/hour</th>
<th>detected events/hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>~33 000</td>
<td>~3000</td>
</tr>
<tr>
<td>6</td>
<td>~10</td>
<td>~2 \times 10^{-2}</td>
</tr>
<tr>
<td>8</td>
<td>~4 \times 10^{-3}</td>
<td>~9 \times 10^{-6}</td>
</tr>
<tr>
<td>10</td>
<td>~1 \times 10^{-6}</td>
<td>~5 \times 10^{-10}</td>
</tr>
</tbody>
</table>

Current single-photon detector technologies

<table>
<thead>
<tr>
<th>Detector</th>
<th>Detection efficiency</th>
<th>Maximum counting rates</th>
<th>Dead time</th>
<th>Jitter time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si avalanche photodiodes (APDs)</td>
<td>65% @ 650 nm</td>
<td>10 MHz</td>
<td>1 ns</td>
<td>400 ps</td>
</tr>
<tr>
<td>InGaAs APDs</td>
<td>10% @ 1.55 µm</td>
<td>10 kHz</td>
<td>10 µs</td>
<td>370 ps</td>
</tr>
</tbody>
</table>

Emerging single-photon detector technologies

<table>
<thead>
<tr>
<th>Detector</th>
<th>Detection efficiency</th>
<th>Maximum counting rates</th>
<th>Dead time</th>
<th>Jitter time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superconducting transition-edge sensors (TESs)</td>
<td>99% @ 1.55 µm</td>
<td>100 kHz</td>
<td>1 µs</td>
<td>100 ns</td>
</tr>
<tr>
<td>Superconducting nanowire single photon detectors (SNSPDs)</td>
<td>93% @ 1.55 µm</td>
<td>GHz</td>
<td>100 ps</td>
<td>40 ps</td>
</tr>
</tbody>
</table>

factor of 2-3 /photon

(~100x for six-photon states)

Superconducting nanowire physics

Operation

Detection cycle

- Bias current $<15 \, \mu A$
- Temperature operation $<1K$
- Dead times $<50 \, \text{ns}$
- Jitter times $<100 \, \text{ps}$

Temperatures 1-4 K

50Ω transmission line

≤200 nm

≤10 nm

NbN nanowire

to current bias and readout electronics

Detection cycle
Optical alignment & Cavity design

Fiber-coupling detector

- Optical fiber
- Coaxial connector pin
- Fiber ferrule
- Zirconia sleeve
- Device chip
- Sapphire rod
- Coaxial connector pin

Miller et al., Opt. Express (2011)

Highest coupling efficiency
Above 99%

Optical stack

- TiO₂
- Au (pads)
- WSi SNSPD
- SiO₂ (sputtered)
- Au (mirror)
- SiO₂ (thermal)
- Si (substrate)

Pseudo optical cavity (1550nm)
Above 95% absorption

Nature Physics 7, 399 (2011)
System detection

Closed-cycle refrigerator

Joule-Thomson stage
Lowest temperature <0.9K
Cooling capacity > 1mW @ 1K

Four-element detector

12 Four-element detector units
above 95% efficiency at telecom-wavelength
(Amorphous tungsten-silicon alloy + pseudo optical cavity)
Photonic Quantum Gates
Path-Encoding: Linear Algebra

$|0\rangle = 01 >$

$|1\rangle = 10 >$

$|0\rangle$ corresponds to $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$

$|1\rangle$ corresponds to $\begin{pmatrix} 0 \\ 1 \end{pmatrix}$

$\alpha_0 |0\rangle + \alpha_1 |1\rangle$ corresponds to $\begin{pmatrix} \alpha_0 \\ \alpha_1 \end{pmatrix}$

$\alpha_0 \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \alpha_1 \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \begin{pmatrix} \alpha_0 \\ \alpha_1 \end{pmatrix}$
Path-Encoding: Linear Algebra

Corresponds to

\[
\begin{pmatrix}
1 & 0 \\
0 & e^{i\varphi}
\end{pmatrix}
\]

Corresponds to

\[
\begin{pmatrix}
i & 1 \\
\sqrt{2} & \sqrt{2} \\
1 & i \\
\sqrt{2} & \sqrt{2}
\end{pmatrix}
\]

Hadamard:

Just a 50/50 beamsplitter!

\[
H = \begin{pmatrix}
1 & 1 \\
1 & -1
\end{pmatrix}
\]
The (linear) ease of single photons

The whole Bloch sphere is accessible with linear optics operations (phase retardation, polarizing and non-polarizing beamsplitters)

Non-polarizing symmetric beam splitter (Hadamard gate)

\[
H = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}
\]

\[
a_{H,V}^{\dagger} \rightarrow \frac{1}{\sqrt{2}} (a_{H,V}^{\dagger} + b_{H,V}^{\dagger})
\]

\[
b_{H,V}^{\dagger} \rightarrow \frac{1}{\sqrt{2}} (a_{H,V}^{\dagger} - b_{H,V}^{\dagger})
\]

\[
H |10\rangle_{ab} = \frac{1}{\sqrt{2}} (|10\rangle_{ab} + |01\rangle_{ab})
\]
Path-Encoding: Single-Qubit Control

corresponds to

\[
\begin{pmatrix}
i \\
\frac{1}{\sqrt{2}} \\
1 \\
\frac{1}{\sqrt{2}} \\
\end{pmatrix}
\begin{pmatrix}
1 & 0 \\
0 & e^{i\phi} \\
\end{pmatrix}
\begin{pmatrix}
i \\
\frac{1}{\sqrt{2}} \\
1 \\
\frac{1}{\sqrt{2}} \\
\end{pmatrix}
\begin{pmatrix}
1 \\
0 \\
\end{pmatrix}
\]
Path-Encoding: Single-Qubit Control

corresponds to the circuit

$$|0\rangle \xrightarrow{H} \xrightarrow{\phi} \xrightarrow{H}$$
- **Requirement:**

\[ |0\rangle \quad \begin{array}{c} \text{U} \end{array} \quad \text{Any state } |\psi\rangle \]

- **Hadamard** and **phase-shift** gates form a **universal** gate set

- **Example:** The following circuit generates

\[ |\psi\rangle = \cos \theta \ |0\rangle + e^{i\phi} \sin \theta \ |1\rangle \] up to a global factor

\[
\begin{array}{c}
\text{H} & \text{2\theta} & \text{H} & \frac{\pi}{2} + \phi \\
\end{array}
\]
Requirement:

\[ |0\rangle \rightarrow U \rightarrow \text{Any state } |\psi\rangle \]
Polarizing Beamsplitter (PBS)

Motivation
Quantum Computing

Quantum Computing @ Uni Wien

Polarizing Beamsplitter (PBS)

Horizontally polarized light

Vertically polarized light

\[ a_H^\dagger \rightarrow a_H^\dagger \]
\[ a_V^\dagger \rightarrow b_V^\dagger \]
PBS

45° Polarized Light
(e.g.: Pol-Filter@45°)

Hadamard via Polarizing Beamsplitters
2-Photon QIP
(two-qubit gates)
The challenge: photon-photon interaction

Control-NOT Gate (Control-X)

\[
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 \\
0 & 0 & 1 & 0
\end{bmatrix}
\rightarrow
\begin{bmatrix}
|H\rangle_c|H\rangle_T \\
|H\rangle_c|V\rangle_T \\
|V\rangle_c|H\rangle_T \\
|V\rangle_c|V\rangle_T
\end{bmatrix}
\]
Control-Phase Gate

- Possible via Kerr-effect
  \[ n_{\text{Kerr}} = n_0 + \chi^{(3)} E^2 \]
- But: 3\textsuperscript{rd} order susceptibility is on the order of \(10^{18} \text{ m}^2/\text{W}\)
- unlikely for single photons
- Some techniques can enhance the nonlinearity significantly (\(~10^2\) -)
  Cavity-QED

\[
K = \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & -1
\end{pmatrix}
\]
Conversion of a C-Phase to C-NOT gate

\[ K = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \]
2-Photon QIP
(two-qubit gates)

-> Effective Nonlinearity via measurement!!!
Fundamental Quantum Interference

Bosonic Input $\rightarrow$ Bunching
(Hong-Ou-Mandel Effect)

$|11\rangle_{ab} \rightarrow H |11\rangle_{ab} = H a^\dagger b^\dagger |00\rangle_{ab}$

Beamsplitter:
$T = 50\%$
$R = 50\%$

Beamsplitter:
$T = 50\%$
$R = 50\%$

Coincidences (in 10 sec)

Flight Time Difference $\tau$ (ps)

Graph:
- $\psi^+$
- Coincidences in 10 sec
- Flight Time Difference $\tau$ (ps)
Measurement of Subpicosecond Time Intervals between Two Photons by Interference

C. K. Hong, Z. Y. Ou, and L. Mandel

Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627
(Received 10 July 1987)

FIG. 1. Outline of the experimental setup.

No. of coincidence counts in 10 min.

Position of beam splitter (μm)
We turn now to the general case with two polarizers set at arbitrary angles $\theta_1$ and $\theta_2$.

\[
P_c(0) \approx \langle \psi | \hat{P}_{\text{pol},1}(\theta_1) \hat{P}_{\text{pol},2}(\theta_2) \hat{P}_{\text{c, red}} \hat{P}_{\text{pol},2}(\theta_2) \hat{P}_{\text{pol},1}(\theta_1) | \psi \rangle_{\Delta x = 0}
\]

\[
= \frac{1}{2} \left[ \langle 1_1 \hat{H}^{1_2} \hat{H}^{1_2} \hat{\phi} \rangle - \langle 1_1 \hat{H}^{1_2} \hat{1_2} | 1_1 \hat{H}^{1_2} \hat{1_2} \rangle | 1_1 \hat{H}^{1_2} \hat{1_2} \rangle (| 1_1 \hat{H}^{1_2} \hat{1_2} \rangle (| 1_1 \hat{H}^{1_2} \hat{1_2} \rangle (| 1_1 \hat{H}^{1_2} \hat{1_2} \rangle (| 1_1 \hat{H}^{1_2} \hat{1_2} \rangle (| 1_1 \hat{H}^{1_2} \hat{1_2} \rangle (\hat{a}_{1_1}^{\dagger} \hat{a}_{1_1}^{\dagger} \hat{a}_{1_2} \hat{a}_{1_2} + \hat{a}_{1_2} \hat{a}_{1_2}^{\dagger} \hat{a}_{1_1}^{\dagger} \hat{a}_{1_1}) \right)
\]

\times (\hat{a}_{1_2} \hat{a}_{1_2} + \hat{a}_{1_2} \hat{a}_{1_2}^{\dagger} \hat{\phi}^{\dagger} \hat{\phi}^{\dagger} \hat{\phi}^{\dagger} \hat{\phi}^{\dagger} \hat{\phi}^{\dagger} \hat{\phi}^{\dagger} \hat{\phi}^{\dagger} \hat{\phi}^{\dagger} \hat{\phi}^{\dagger} \hat{\phi}^{\dagger} \hat{\phi}^{\dagger} \hat{\phi}^{\dagger} \hat{\phi}^{\dagger} \hat{\phi}^{\dagger} \hat{\phi}^{\dagger} \hat{\phi}^{\dagger} \hat{\phi}^{\dagger} \hat{\phi}^{\dagger} \hat{\phi}^{\dagger} \hat{\phi}^{\dagger} \hat{\phi}^{\dagger})
\]

Using Eq. (A2), one can expand $| \tilde{\psi} \rangle_{\Delta x = 0} = \hat{P}_{\text{pol},2}(\theta_2) \hat{P}_{\text{pol},1}(\theta_1) | \psi \rangle_{\Delta x = 0}$. After simplifying algebra one finds

\[
| \tilde{\psi} \rangle_{\Delta x = 0} = |1_1 \hat{H}^{1_2} \rangle \cos \theta_1 \cos \theta_2 \sin(\theta_2 - \theta_1) \sin \phi + \langle 1_1 \hat{V}^{1_2} \rangle \sin \theta_1 \sin \theta_2 \sin(\theta_2 - \theta_1) \sin \phi
\]

\[
+ \langle 1_1 \hat{V}^{1_2} \rangle \cos \theta_1 \sin \theta_2 \sin(\theta_2 - \theta_1) \sin \phi + \langle 1_1 \hat{H}^{1_2} \rangle \sin \theta_1 \cos \theta_2 \sin(\theta_2 - \theta_1) \sin \phi.
\]

It then follows that

\[
P_c(0) \approx \langle \psi | \hat{P}_{\text{c, red}} | \tilde{\psi} \rangle_{\Delta x = 0} = \sin^2 \phi \sin^2(\theta_2 - \theta_1),
\]

which is the more general case of Eq. (13).
Tuning Quantum Interference for 2-Photon Gates

\[ \text{Beamsplitter:} \quad T = 33\% \quad R = 67\% \]

\[ \begin{align*}
+ & = -1/9 \\
\end{align*} \]

Sometimes \((1/9)\): 2-fold-coincidences \(\rightarrow\) these events have a \((-1)\) phase !!!
Success probability: $p=1/9$

Destructive (required to measure output)

Integrated Optics for Path-Encoded C-NOT

Polarization-Encoded Photons: 2-photon gate is simplified

\[ a_H^\dagger b_H^\dagger \text{PDBS}_0 \rightarrow a_H^\dagger b_H^\dagger \text{PDBS}_{a,b} \rightarrow \frac{1}{3} a_H^\dagger \sqrt{\frac{1}{3}} b_H^\dagger = \frac{1}{9} a_H^\dagger b_H^\dagger \]

\[ a_H^\dagger b_V^\dagger \text{PDBS}_0 \rightarrow a_H^\dagger b_V^\dagger \text{PDBS}_{a,b} \rightarrow \frac{1}{3} a_H^\dagger \sqrt{\frac{1}{3}} b_V^\dagger = \frac{1}{9} a_H^\dagger b_V^\dagger \]

\[ a_V^\dagger b_H^\dagger \text{PDBS}_0 \rightarrow a_V^\dagger b_H^\dagger \text{PDBS}_{a,b} \rightarrow \frac{1}{3} a_V^\dagger \sqrt{\frac{1}{3}} b_H^\dagger = \frac{1}{9} a_V^\dagger b_H^\dagger \]

\[ a_V^\dagger b_V^\dagger \text{PDBS}_0 \rightarrow a_V^\dagger b_V^\dagger + i \frac{2}{3} a_V^\dagger a_V^\dagger b_V^\dagger \text{PDBS}_{a,b} \rightarrow \frac{1}{3} a_V^\dagger b_V^\dagger - \frac{2}{3} a_V^\dagger b_V^\dagger = -\frac{1}{9} a_V^\dagger b_V^\dagger \]

\[
\begin{align*}
\text{PDBS}_0: & \quad \begin{cases} 
a_H^\dagger \rightarrow a_H^\dagger \\
 a_V^\dagger \rightarrow \sqrt{\frac{1}{3}} a_V^\dagger + i \sqrt{\frac{2}{3}} b_V^\dagger \\
b_H^\dagger \rightarrow b_H^\dagger \\
b_V^\dagger \rightarrow \sqrt{\frac{1}{3}} b_V^\dagger + i \sqrt{\frac{2}{3}} a_V^\dagger 
\end{cases} \\
\text{PDBS}_a: & \quad \begin{cases} 
a_H^\dagger \rightarrow \sqrt{\frac{1}{3}} a_H^\dagger + i \sqrt{\frac{2}{3}} c_H^\dagger \\
a_V^\dagger \rightarrow a_V^\dagger 
\end{cases} \\
\text{PDBS}_b: & \quad \begin{cases} 
b_H^\dagger \rightarrow \sqrt{\frac{1}{3}} b_H^\dagger + i \sqrt{\frac{2}{3}} d_H^\dagger \\
b_V^\dagger \rightarrow b_V^\dagger 
\end{cases}
\end{align*}
\]
Integrated C-NOT (C-Phase) Gate

Crespi et al., Nature Communications 2, 566 (2011)
Quantum Simulation Using Photons

Philip Walther
Faculty of Physics
University of Vienna
Austria

Enrico Fermi Summer School
Varenna, Italy
24-25 July 2016
Lecture II:
Non-destructive / scalable photonic quantum gates & Photonic Quantum Simulation
Non-destructive two-qubit gates via extra (ancilla) photons
Non-Destructive C-NOT gate

\[
\begin{align*}
|H\rangle_C |H\rangle_T & \rightarrow |H\rangle_C |H\rangle_T \\
|H\rangle_C |V\rangle_T & \rightarrow |H\rangle_C |V\rangle_T \\
|V\rangle_C |H\rangle_T & \rightarrow |V\rangle_C |V\rangle_T \\
|V\rangle_C |V\rangle_T & \rightarrow |V\rangle_C |H\rangle_T \\
|H \pm V\rangle_C |H\rangle_T & \rightarrow |H\rangle_C |H\rangle_T \pm |V\rangle_C |V\rangle_T
\end{align*}
\]

- Concept of using extra (ancilla) photons
Non-Destructive C-NOT gate

- Concept of using extra (ancilla) photons
- CNOT gate works correctly if one photon exits in each mode
- Probabilistic gate with 25% chance of success

\[
\begin{align*}
|H\rangle_C |H\rangle_T & \rightarrow |H\rangle_C |H\rangle_T \\
|H\rangle_C |V\rangle_T & \rightarrow |H\rangle_C |V\rangle_T \\
|V\rangle_C |H\rangle_T & \rightarrow |V\rangle_C |V\rangle_T \\
|V\rangle_C |V\rangle_T & \rightarrow |V\rangle_C |H\rangle_T \\
|H \pm V\rangle_C |H\rangle_T & \rightarrow |H\rangle_C |H\rangle_T \pm |V\rangle_C |V\rangle_T
\end{align*}
\]

Gasparoni, Pan, Walther, Rudolph, Zeilinger, PRL 93, 020504 (2004)
Franson, Jacobs, Pittman, PRA 70, 062302 (2004)
Polarizing Beamsplitter (PBS) II

PBS: parity-check polarization ↔ path

Motivation

Quantum Computing @ UniWien

Polarizing Beamsplitter (PBS) II
Quantum Encoder („duplicator“)

1AO1 Photon

\[ \alpha |H\rangle_C + \beta |V\rangle_C \rightarrow \alpha |H\rangle_A |H\rangle_B + \beta |V\rangle_A |V\rangle_B \]

superposition → entanglement

Motivation
Quantum Computing

Quantum Encoder ("duplicator")

P=1/2
Destructive C-NOT

\[ |H\rangle_C |H\rangle_T \rightarrow |\Phi^+\rangle_{45} \rightarrow |\Phi^+\rangle_{H/V} \Rightarrow |H\rangle_B \]

\[ |H\rangle_C |V\rangle_T \rightarrow |\Phi^-\rangle_{45} \rightarrow |\Psi^+\rangle_{H/V} \Rightarrow |V\rangle_B \]

\[ |V\rangle_C |H\rangle_T \rightarrow |\Phi^-\rangle_{45} \rightarrow |\Psi^+\rangle_{H/V} \Rightarrow |V\rangle_B \]

\[ |V\rangle_C |V\rangle_T \rightarrow |\Phi^+\rangle_{45} \rightarrow |\Phi^+\rangle_{H/V} \Rightarrow |H\rangle_B \]
16 correlation measurements:
Fidelity = 81%

From separable to entangled
Fidelity = 77%

Q: Great!
  Measurements give me two-qubit gates.

Q: But!
  Isn’t a probabilistic gate a killer?
  Just 20 gates, ...and I get success rate of $(1/2)^{20}$

A: Solution is existing! Read:
  1) Gottesmann & Chuang (Nature 1999) and
  2) Knill, Laflamme, Milburn (Nature 2001)

A: Basically, take more photons and smart scheme to achieve deterministic gates
Teleportation Trick for achieving scalability

How can we apply probabilistic gates in a circuit without losing scalability?

Effective non-linearities via measurement
\[ \rightarrow 10^3 - 10^5 \text{ extra (ancilla photons) per qubit} \]

Knill, Laflamme, Milburn, Nature 409, 46 (2001)
Experimental setup for two consecutive CNOTS.
Experimental setup for two consecutive CNOTS

- Polarization Dependent Beam Splitter
- Polarizing Beam Splitter
- Polarization controller
- Local Unitary
- BBO crystal
- QWP
- HWP

Solving systems of linear equations on a quantum computer
Barz, Kassal, Lipp, Ringbauer, Aspuru-Guzik, Walther
Scientific Reports 4, 6115 (2014)
Show Movie!
Deterministic Photonic Quantum Gates
(some examples)
Example 1: Boosting the Kerr effect

Control-Phase Gate

- Possible via Kerr-effect

\[ n_{\text{Kerr}} = n_0 + \chi^{(3)} E^2 \]

- But: 3\textsuperscript{rd} order susceptibility is on the order of \(10^{18} \text{ m}^2/\text{W}\)

- unlikely for single photons

- Some techniques can enhance the nonlinearity significantly (\(\sim10^2\)) -> Cavity-QED

\[
K = \begin{pmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & -1
\end{pmatrix}
\]
Cavity QED for deterministic phase gates

- whispering gallery mode (WGM) resonator (Bottle resonator\(^1\))
- \(^{85}\text{Rb}\) atom is trapped in the evanecent field of the guide moded
- nearly lossless fiber coupling and high Q-factor (\(\sim 10^8\)) tuned to an EIT \(^{85}\text{Rb}\) atom’s transition.

- single photons tuned to the \(^{85}\text{Rb}\) transition (\(\sim 8\) MHz @ 780nm)
- conditional phase-shift of \(\pi\) for single photons
  (phase-shifts already seen by using faint coherent light [Rauschenbeutel Group, Vienna\(^2\)])

References:

Example 2: Suppression of failure events in gates

- CNOT gate works correctly if one photon exits in each mode.
- All failure events are due to 2 photons leaving in the same path.
- Failure events can be suppressed by frequent observations to determine if two photons are present in the same output path → Quantum Zeno effect.

- Emission of two photons into the same fiber can be inhibited by frequent measurements to see if 2 photons are there → 1 photon passes, but 2 photons are absorbed → strong 2-photon absorption (e.g. via atoms in fibers).

Quantum computing using single photons and the Zeno effect
J.D. Franson, B.C. Jacobs, T.B. Pittman, PRA 70, 062302 (2004)
Photonic Quantum Simulation
Richard Feynman

The real problem is simulating quantum mechanics

Hopeless task on a classical computer

Let’s use quantum systems as computational building blocks!

Seth Lloyd

Feynman was correct, for very large class of physical quantum systems

Given initial wavefunction,

No. qubits required ∝ poly(No. particles)

Time evolution operator,

No. gates required ∝ poly(particles)

discrete gate operations

\[ |\psi_1\rangle \quad U \quad U \quad m_1 \]

\[ |\psi_2\rangle \quad U \quad U \quad m_2 \]

\[ |\psi_3\rangle \quad U \quad U \quad m_3 \]

\[ |\psi_4\rangle \quad U \quad U \quad m_4 \]

Time

- same evolution as in Nature
- can be adiabatic (or not)
Analog Quantum Simulator

- same evolution as in Nature
- can be adiabatic (or not)

Global Challenge:
 to build a quantum simulator for studying other quantum systems

Benefit and Impact:
 providing a means of exploring new physical phenomena in many fields

General Advantage:
 Quantum simulators are less demanding! (~40 qubits)

Advantages of Photons:
- generation of complex multi-photon entanglement
- use mobility of photons as key advantage
- scalable processing via light-matter interactions
Analog Quantum Simulation of Heisenberg-Interacting Spins
Chemical Bonds = Singlet States

Hydrogen atom:  

\[ \uparrow \]

Hydrogen molecule:

\[ \begin{align*}
\begin{array}{c}
\uparrow \\
\downarrow
\end{array}
\end{align*} = \frac{1}{\sqrt{2}} (| \uparrow \downarrow \rangle - | \downarrow \uparrow \rangle) \]
Quantum Information in Quantum Chemistry

Chemical Bonds = Singlet States

Hydrogen atom: \( |\uparrow\rangle \)

Hydrogen molecule:

\[
\begin{align*}
\frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)
\end{align*}
\]

Photonic Quantum Chemistry

\[
k_{\text{pump}} = k_{\text{photon1}} + k_{\text{photon2}}
\]

\[
w_{\text{pump}} = w_{\text{photon1}} + w_{\text{photon2}}
\]

Aspuru-Guzik, Walther

Ma, Dakic, Walther
Quantum Information in Valence Bonds

Valence Bond Solids (VBS)

Entangled Spin Liquid: Resonating Valence Bonds (RVB)

\[ \frac{1}{\sqrt{2}} (|↑↓⟩ - |↓↑⟩) \]

Fazekas, Anderson, Phil Mag 30, 23 (1974)
Solid State Physics

Valence Bond Solids (VBS)

Entangled Spin Liquid: Resonating Valence Bonds (RVB)

Quantum Chemistry

- Resonance leads to a symmetric configuration of valence bonds (Kekulé, Pauling)
- Aromatic systems and anti-aromatic systems (Hückel)

Fazekas, Anderson, Phil Mag 30, 23 (1974)
Quantum Simulation Tasks:

- simulation of frustrated spin systems
- paired short-range singlets: insulating spin liquid ground states of Mott insulators
- mobile insulating states: Anderson’s conjecture for superconductivity in cuprates
- simulation of s-wave pairing symmetry for valence bond states

\[
\begin{bmatrix}
\begin{array}{c}
\text{s} \\
\end{array}
\end{bmatrix} = \frac{1}{\sqrt{3}} \left( \begin{array}{c}
\begin{array}{cc}
\text{plus} \\
\end{array}
\end{array} + 
\begin{array}{c}
\begin{array}{c}
\text{state}
\end{array}
\end{array} \right)
\]

- simulation of exotic d-wave pairing symmetry for valence bond states

\[
\begin{bmatrix}
\begin{array}{c}
\text{d} \\
\end{array}
\end{bmatrix} = \begin{array}{cc}
\text{minus} \\
\end{array} +
\begin{array}{c}
\begin{array}{c}
\text{state}
\end{array}
\end{array}
\]


Mambrini, Läuchli, Poilblanc, Mila, PRB 74, 144422 (2006)

Ground state of a quantum anti-ferromagnet

- absolute ground state has total spin-zero (Marshall’s theorem) on a bipartite lattice with nearest neighbor Heisenberg-type interactions

- antiferromagnetically interacting spins form spin-zero singlet states

\[
\Phi_\parallel \equiv |\psi^-\rangle_{13} |\psi^-\rangle_{24} \\
\Phi_\perp \equiv |\psi^-\rangle_{12} |\psi^-\rangle_{34}
\]

- total spin-zero subspace is 2-dimensional \(\rightarrow\) only 2 independent dimer-covering states: 

\[
|\Phi_\times\rangle \equiv |\psi^-\rangle_{14} |\psi^-\rangle_{23}
\]

- Static and localized dimer-covering states \(\rightarrow\) valence bond solids

- Dimer-covering states fluctuating as superpositions \(\rightarrow\) valence bond liquids

\[
|\Phi_\times\rangle = |\Phi_\parallel\rangle - |\Phi_\perp\rangle \\
|\Phi_\parallel\rangle + |\Phi_\perp\rangle + |\Phi_\times\rangle
\]

Requirements for the quantum simulation of valence bond (liquid) states

\[ H = J_1 (\mathbf{S}_1 \cdot \mathbf{S}_3 + \mathbf{S}_2 \cdot \mathbf{S}_4) + J_2 (\mathbf{S}_1 \cdot \mathbf{S}_2 + \mathbf{S}_3 \cdot \mathbf{S}_4) \]

- capability of preparing arbitrary superpositions of dimer-covering states is sufficient for simulating any Heisenberg-type interaction of four spin-1/2 particles on a square lattice

- strength of optical quantum simulators that the simulated ground states can be restricted to the spin-zero singlet subspace; e.g. by utilizing the quantum interference at a controllable beam splitter
Simulation of a Heisenberg spin-1/2 tetramer using a photonic AQS

\[ H = J_1 \left( \vec{S}_1 \vec{S}_3 + \vec{S}_2 \vec{S}_4 \right) + J_2 \left( \vec{S}_1 \vec{S}_2 + \vec{S}_3 \vec{S}_4 \right) \]
Simulation of a Heisenberg spin-1/2 tetramer using a photonic AQS

\[ H = J_1 \left( \vec{S}_1 \vec{S}_3 + \vec{S}_2 \vec{S}_4 \right) + J_2 \left( \vec{S}_1 \vec{S}_2 + \vec{S}_3 \vec{S}_4 \right) \]

- Initial ground state: entangled photon pairs 1 & 2 and 3 & 4

\[ H(\kappa) = \frac{H}{J_1} = H_0 + \kappa H_1 \]

\[ \tan^2 \theta = \kappa + \sqrt{\kappa^2 - \kappa + 1} \]
Simulation of a Heisenberg spin-1/2 tetramer using a photonic AQS

\[ H = J_1 \left( \vec{S}_1 \cdot \vec{S}_3 + \vec{S}_2 \cdot \vec{S}_4 \right) + J_2 \left( \vec{S}_1 \cdot \vec{S}_2 + \vec{S}_3 \cdot \vec{S}_4 \right) \]

Initial ground state: entangled photon pairs 1 & 2 and 3 & 4

\[ H(\kappa) = \frac{H}{J_1} = H_0 + \kappa H_1 \]

\[ \tan^2 \theta = \kappa + \sqrt{\kappa^2 - \kappa + 1} \]

Tunable interaction: superimposing photons 1 & 3 on a tunable beam splitter

#### VBS states: paired short-range singlets:
insulating spin liquid ground states of Mott insulators

#### RVB states (Spin Liquid): mobile insulating states:
Anderson's conjecture for superconductivity in cuprates

s-wave pairing

d-wave pairing

*Anderson, Science 235, 1196 (1987)*

*Trebst, Schollwöck, Troyer, Zoller, PRL 96, 250402 (2006)*
Sources:

- a pulsed ultraviolet laser : 404 nm, 180 fs, 80 MHz
- Type-II SPDC from two BBO crystals

Measurement-induced interaction

- tunable directional coupler (TDC)
Beamsplitter as Singlet-State Filter

\[ |\Psi^-\rangle = \frac{1}{\sqrt{2}} (|H\rangle_1 |V\rangle_2 - |V\rangle_1 |H\rangle_2) \]

\[
\begin{array}{c}
\text{D1} \\
\text{D2} \\
& \& \\
C
\end{array}
\]

Coincidences (in 10 sec) vs. Flight Time Difference \( \tau \) (ps)
Tuning the ground state and its energy

\[ |\Psi^0(\theta)\rangle = \frac{1}{\sqrt{n(\theta)}} (\cos 2\theta |\uparrow\rangle - \cos^2 \theta |\downarrow\rangle) \]
Entanglement Dynamics of VB States

- Tomographic reconstruction of each ground state density matrix
- Eight different ground states (10.368 coincidence counts)
- High quantum-state fidelities (average of $F \sim 0.80$)
- Extraction of total energy
- Extraction of pair-wise Heisenberg energy

\[ E^0 = -2(\kappa + 1) + 4\sqrt{\kappa^2 - \kappa + 1} \]

\[ |\Psi^0(\theta)\rangle = \frac{1}{\sqrt{n(\theta)}} \left( \cos 2\theta |\downarrow\rangle - \cos^2 \theta |\uparrow\rangle \right) \]
And what could we learn?
Quantum Monogamy and Complementarity Relations

- characterization of the two-body energies and correlations
- normalized Heisenberg energy per unit of interaction
  \[ e_{ij} = -\frac{1}{3} Tr(\rho_{ij} \vec{S}_i \vec{S}_j) \]
- constraint of energy distribution through complementarity relation
  \[ e_{12}^2 + e_{13}^2 + e_{14}^2 = 1 \]

Observation of quantum monogamy
1. restricts the sharability of quantum correlations among multiple parties
2. leads to frustration effects in condensed-matter physics

Ma, Dakic, Naylor, Zeilinger, Walther, Nature Physics 7, 399 (2011)
Can we get insights into ground states in the thermodynamical limit?

Yes!

- access to nearest and next-nearest neighbor interactions
- more additional tunable beamsplitters

Ma, Dakic, Kropatschek, Naylor, Chan, Gong, Zeilinger, Duan, Walther
Scientific Reports 4, 3583 (2014)
Quantum Simulation Using Photons

Philip Walther

Faculty of Physics
University of Vienna
Austria

Enrico Fermi Summer School
Varenna, Italy
24-25 July 2016
Lecture III:
Photonic Quantum Simulation &
Quantum computing exploiting the
superposition of quantum gates
Digital Quantum Simulation of 2 XY-interacting Spins
Quantum Simulation of XY-interacting Spins

- Simulation of a two-qubit XY Heisenberg Hamiltonian in a transverse magnetic field

\[
H = J_x \sigma_x \otimes \sigma_x + J_y \sigma_y \otimes \sigma_y + \frac{1}{2} B (\mathbb{1} \otimes \sigma_z + \sigma_z \otimes \mathbb{1})
\]

- Transformation to non-interacting particles (diagonal from) by applying \( U \)

\[
U = \begin{pmatrix}
\cos \frac{x}{2} & 0 & 0 & \sin \frac{x}{2} \\
0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\
0 & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\
-\sin \frac{x}{2} & 0 & 0 & \cos \frac{x}{2}
\end{pmatrix}
\]

with: \( \tan x = \frac{J_x - J_y}{B} \)

- Allows to obtain free particle Hamiltonian

\[
UHU^\dagger = \omega_1 \sigma_z \otimes \mathbb{1} + \omega_2 \mathbb{1} \otimes \sigma_z
\]

free particle energy:

\[
\omega_1 = \frac{1}{2} (E_1 - \hat{E}_2) \\
\omega_2 = \frac{1}{2} (E_1 + E_2)
\]

Aspuru-Guzik group

Verstraete, Cirac, Latorre, PRA 79, 032316 (2009)
Quantum Simulation of XY-interacting Spins

- With $U$ we get access to ground and excited eigenstates of $H |\psi_i\rangle = E_i |\psi_i\rangle$

  $|\psi_1\rangle = U |00\rangle$
  $|\psi_2\rangle = U |01\rangle$
  $|\psi_3\rangle = U |10\rangle$
  $|\psi_4\rangle = U |11\rangle$

  $|\psi_1\rangle = \cos \frac{x}{2} |00\rangle + \sin \frac{x}{2} |11\rangle$, $E_1 = \sqrt{B^2 + (J_x - J_y)^2}$
  $|\psi_2\rangle = \frac{1}{\sqrt{2}} (|01\rangle - |10\rangle)$, $E_2 = -J_x - J_y$
  $|\psi_3\rangle = \frac{1}{\sqrt{2}} (|01\rangle + |10\rangle)$, $E_3 = J_x + J_y$
  $|\psi_4\rangle = -\sin \frac{x}{2} |00\rangle + \cos \frac{x}{2} |11\rangle$, $E_4 = -\sqrt{B^2 + (J_x - J_y)^2}$

- Quantum Circuit to implement $U$

  ![Quantum Circuit Diagram]

  - local Bogolubov transformations
  - also for thermal states: $\rho_{th} = e^{-\frac{H}{kT}} = U e^{-\frac{\hat{H}}{kT}} U^\dagger$
Quantum Simulation of XY-interacting Spins

\[ U = |\psi^\pm\rangle = |\phi^\pm\rangle \]

\[ R_y(\frac{\pi}{2} + \frac{\pi}{4}) \]

\[ R_y(-\frac{\pi}{2} + \frac{\pi}{4}) \]

\[ Z \]

\[ Y \]

\[ W \]

\[ |\psi_1\rangle = \cos \frac{\theta}{2} |00\rangle + \sin \frac{\theta}{2} |11\rangle \]

\[ |\psi_2\rangle = \frac{1}{\sqrt{2}} (|01\rangle + |10\rangle) \]

\[ |\psi_3\rangle = \frac{1}{\sqrt{2}} (|01\rangle - |10\rangle) \]

\[ |\psi_4\rangle = -\sin \frac{\theta}{2} |00\rangle + \cos \frac{\theta}{2} |11\rangle \]
Ressource-Efficient Intermediate Quantum Computing (Boson Sampling)
Multi-Photon Random Walk Computation

Complex Random Walks / N-port interferometers

Transformation of input state to output state (for 2 photons)

\[ U = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \quad \text{and} \quad BS = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix} \]

\[ Perm = \begin{pmatrix} a & b \\ c & d \end{pmatrix} = (ad + cb) \]

\[ P = \left| Perm \begin{pmatrix} T & iR \\ iR & T \end{pmatrix} \right|^2 = \left| T^2 - R^2 \right|^2 \]

Reck, Zeilinger, Bernstein, Bertani, PRL 73, 58 (1994)

Classical limit for boson sampling: ~20 photons in ~400 modes (!)
Photon Interference using Waveguides
Intermediate Photonic Quantum Computing

classical limit for boson sampling: \(\sim 20\) photons in \(\sim 400\) modes (!)

among the hottest candidates for outperforming classical computers
Non-ideal Boson Sampling
Photon Distinguishability

\[ P_{11}(\Delta \tau) = \frac{1}{2} \left( |\text{per}(B)|^2 + |\text{det}(B)|^2 \right) \]

\[ + \, \zeta e^{-\xi \Delta \tau^2} \left( |\text{per}(B)|^2 - |\text{det}(B)|^2 \right) \]
Distinguishability can always be treated as mode-mismatch

One parameter to model them all
Photon Distinguishability

\[ P_e \]

\[ \det(B) \]
Tuning of a BosonSampling Computer

Δτ₁ → Δτ₂

Generalized Multiphoton Quantum Interference
Tillmann, Tan, Stöckl, Sanders, de Guise, Heilmann, Nolte, Szameit, Walther
60 terms describe the interference of a 3-photon landscape

- Overlap-terms weight the per, det and imm

- For perfect indistinguishability this reduces to just the per
Application to larger scattering networks - BosonSampling
Mobility as feature for the speed-up of particular tasks for quantum computers/simulators
Superposition of Quantum Circuits

Quantum switch\(^1\)

\[
\begin{align*}
|\text{PBS}\rangle & \rightarrow (U_1|\text{PBS}\rangle + U_2|\text{PBS}\rangle) \\
|+\rangle_1 & \rightarrow (U_1|\text{PBS}\rangle + U_2|\text{PBS}\rangle) \\
|\psi\rangle_2 & \rightarrow (U_1|\text{PBS}\rangle + U_2|\text{PBS}\rangle)
\end{align*}
\]

Proposal\(^2\)

\[
\begin{align*}
|\text{PBS}\rangle & \rightarrow (U_1|\text{PBS}\rangle + U_2|\text{PBS}\rangle) \\
|+\rangle_1 & \rightarrow (U_1|\psi\rangle + U_2|\psi\rangle) \\
|\psi\rangle_2 & \rightarrow (U_1|\psi\rangle + U_2|\psi\rangle)
\end{align*}
\]


Superposition of Quantum Circuits

Quantum switch\(^1\)

Proposal\(^2\)

---


Superposition of Quantum Circuits

Computational Benefit:

- **exponential advantage** over classical algorithms
- **linear advantage** over quantum algorithms.

Fundamental Interest:

- superposition of **causal order**

---


The task is to distinguish whether a pair of unitary transformations $A$ and $B$ commute or anti-commute.

$$|\psi\rangle|H\rangle \rightarrow BA|\psi\rangle|H\rangle$$

$$|\psi\rangle|V\rangle \rightarrow AB|\psi\rangle|V\rangle$$

$$|\psi\rangle|D\rangle \rightarrow \frac{1}{\sqrt{2}} (BA|\psi\rangle|H\rangle + AB|\psi\rangle|V\rangle)$$

$$|\psi\rangle|D\rangle \rightarrow \frac{1}{\sqrt{2}} (\{A, B\}|\psi\rangle|D\rangle + [A, B]|\psi\rangle|A\rangle)$$
The Experimental Set-Up

DM  Dichroic Mirror
BS  Beamsplitter
LP  Long-pass Filter
BP  Band-pass Filter
POL Polarizer
HWP Half Waveplate
QWP Quarter Waveplate
FC  Fiber Coupler/Collimator
PDM Piezo-Driven Mirror
APD Avalanche Photodiode
PBS Polarizing Beamsplitter
dHWP Dual-Wavelength Half Waveplate
dPBS Dual-Wavelength Polarizing Beamsplitter
Experimental Results

Surpassing regular QC:

- 100 different pairs of unitary gates for determining if 2 random gates commute
- average success rate: 0.976 ± 0.015

Procopio, Moqanaki, Araujo, Costa, Calafell, Dowd, Hamel, Rozema, Brukner, Walther
Nature Communication 6, 8913 (2015)
Summary & Outlook

✅ Quantum monogamy plays a key role in spin frustration
   - quantum simulation of valence-bond solids/liquids
   - observation of quantum monogamy [Nature Physics 7, 399 (2011)]
   - [Nature Physics 8, 285 (2012)]

✅ Quantum simulation of XY-interacting Spins
   - quantum simulation of level crossing [Physical Review X 5, 021010 (2015)]

✅ Intermediate quantum computing
   - experimental boson sampling [Nature Photonics 7, 540 (2013)]

✅ Non-ideal intermediate quantum computing
   - experimental immanent sampling [Physical Review X 5, 041015 (2015)]

✅ Superposition of quantum gates
   - speed-up for regular quantum computers [Nature Communications 6, 8913 (2015)]

⊙ Outlook: Small-scale quantum computing (< 20 photons)
   - superconducting detectors
   - low-loss waveguides
   - novel nonlinear photon sources and multiplexing techniques
   - entanglement in more degrees-of-freedom

⊙ Outlook: Truly scalable quantum photonics
   - deterministic phase gates via light-matter quantum systems
   - graphene-based photon sources
   - solid-state emitters of entangled photons

Thank you for your attention!
Thank you!