Sparse interferometry for measuring multiphoton collective phase

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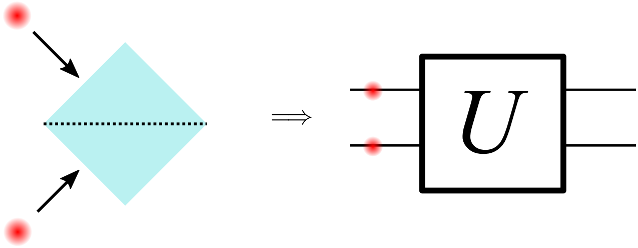
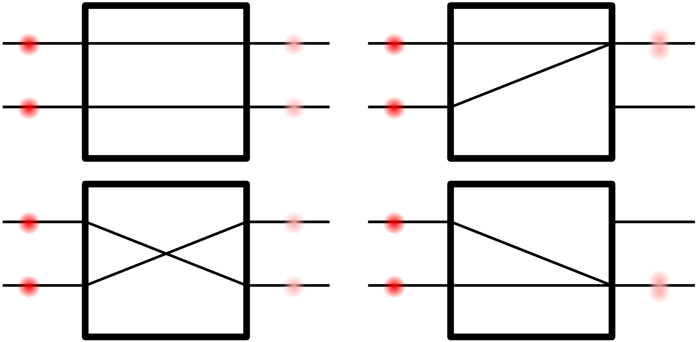
Two-photon interference I

Interference between two indistinguishable photons



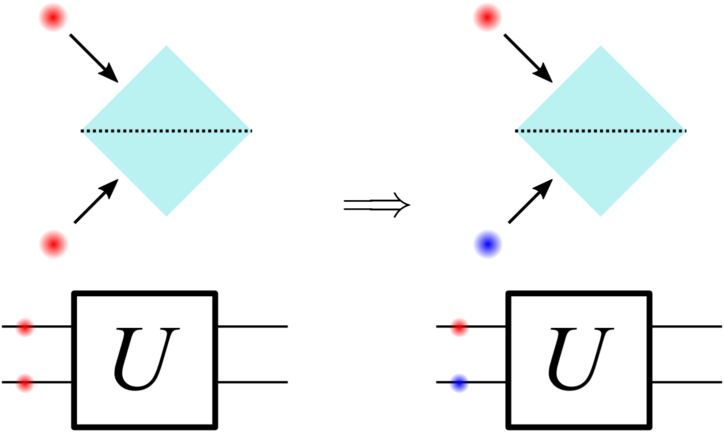
Two-photon interference II

Boson bunching



Two-photon interference III

Interference between two distinguishable photons



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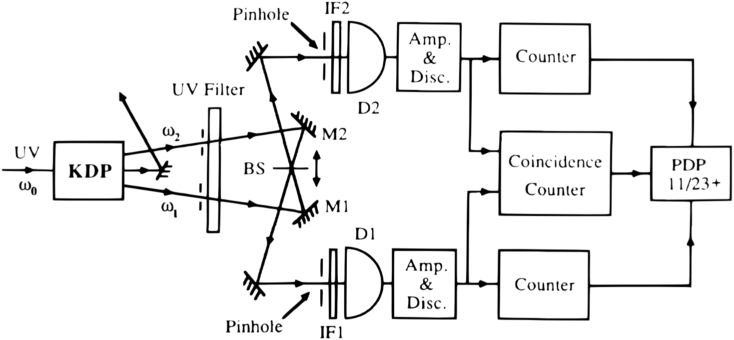
Two-photon interference IV

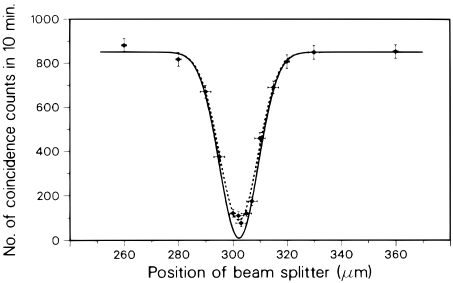
Hong-Ou-Mandel interference



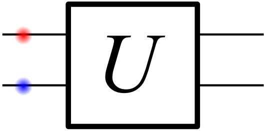
Hong, Ou, Mandel, PRL, 1987: 10/d564wh

Two-photon interference V

Hong-Ou-Mandel dip



Hong, Ou, Mandel, PRL, 1987: 10/d564wh

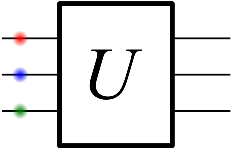


Two-photon coincidence

$$P_{1,1} = \frac{1}{2}\left(1 - |\langle \text{●} \mid \text{●} \rangle|^2\right)$$

Multiphoton interference and collective phase I

Three-photon interference in a tritter



Tritter:

$$U_{i,j} = \mathrm{e}^{\mathrm{i}\frac{2\pi}{3}(i-1)(j-1)}$$

Three-photon phase:

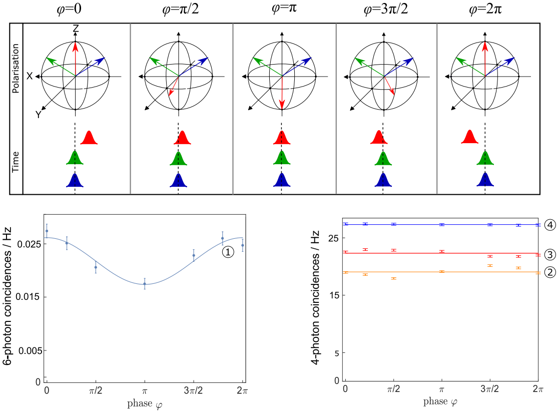
$$\varphi := \arg\left(\langle \textcolor{red}{\bullet} | \textcolor{blue}{\bullet} \rangle \langle \textcolor{blue}{\bullet} | \textcolor{green}{\bullet} \rangle \langle \textcolor{green}{\bullet} | \textcolor{red}{\bullet} \rangle\right)$$

Three-photon coincidence:

$$P_{1,1,1} = \frac{1}{9}\Big[2 + 4\left|\langle \textcolor{red}{\bullet} | \textcolor{blue}{\bullet} \rangle \langle \textcolor{blue}{\bullet} | \textcolor{green}{\bullet} \rangle \langle \textcolor{green}{\bullet} | \textcolor{red}{\bullet} \rangle\right| \cos\varphi - \left|\langle \textcolor{red}{\bullet} | \textcolor{blue}{\bullet} \rangle\right|^2 - \left|\langle \textcolor{blue}{\bullet} | \textcolor{green}{\bullet} \rangle\right|^2 - \left|\langle \textcolor{green}{\bullet} | \textcolor{red}{\bullet} \rangle\right|^2\Big]$$

Multiphoton interference and collective phase II

Collective phase emergent in multiphoton interference



Menssen et al, PRL, 2017: 10/f95dqb

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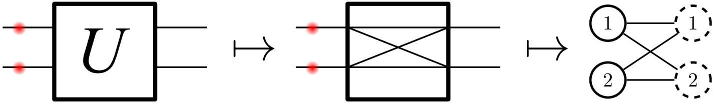
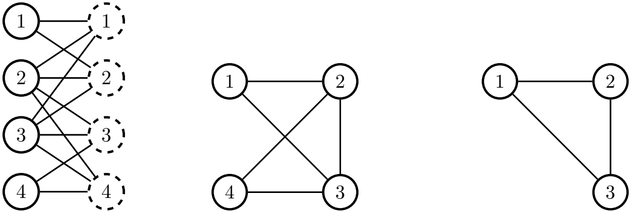
Mapping the interference to graphs

Mapping of a lossless interferometer



Mapping of the interference terms

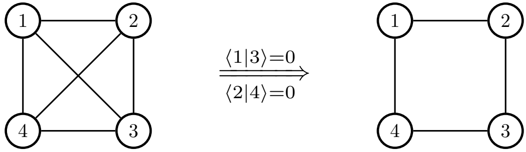


Connectivity graph

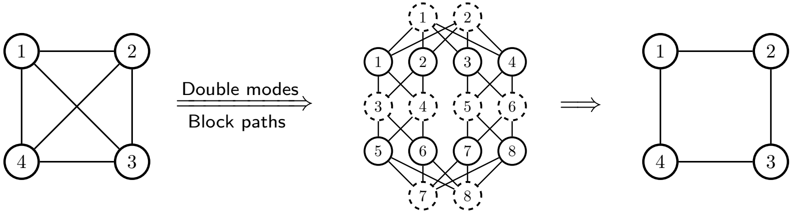
Enhanced-distinguishability graph

How to generate the ED graph with only a circle-n?

Method I: Orthogonalize pairs of photons

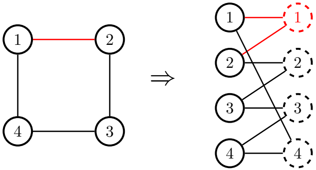


Method II: Sparsify the interferometer



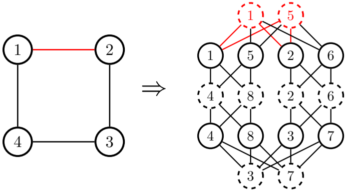
Why should we double the mode number?

If there is one output mode is connected between two input modes



$$\Rightarrow \begin{bmatrix} w_{1,1} & w_{1,2} & 0 & 0 & \cdots & 0 & 0 \\ 0 & w_{2,2} & w_{2,3} & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & w_{n-1,n-1} & w_{n-1,n} \\ w_{n,1} & 0 & 0 & 0 & \cdots & 0 & w_{n,n} \end{bmatrix}$$

Double the mode number



$$\Rightarrow \begin{bmatrix} \cdots & w_{i-1,i} & w_{i,i} & 0 & \cdots & w_{n+i,i} & \cdots \\ \cdots & 0 & w_{i,i+1} & w_{i+1,i+1} & \cdots & w_{n+i,i+1} & \cdots \end{bmatrix}^\top$$

Unitarity constraint

$$w^*_{i+1,i} w_{i+1,i+1} + w^*_{i+1,i} w_{n+i,i+1} = 0$$

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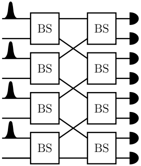
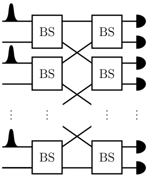
What does the interferometer look like?

Sparse interferometer for four photons



$$U = \frac{1}{2}\begin{bmatrix} 1 & -1 & -1 & 1 & 0 & 0 & 0 & 0 \\ 1 & -1 & 1 & -1 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & -1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 & -1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 0 & 1 & 1 & -1 & -1 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 \end{bmatrix}$$

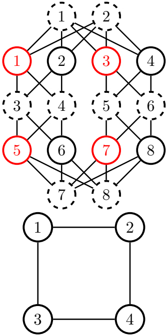
Sparse interferometer for n photons



$$U = \frac{1}{2}\begin{bmatrix} K & L & 0 & \cdots & \cdots & \cdots & 0 \\ J & 0 & L & \ddots & \ddots & \ddots & \vdots \\ 0 & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & J & 0 & L \\ 0 & \cdots & \cdots & \cdots & 0 & J & -K^\top \end{bmatrix} \in \mathrm{U}(2n)$$

How to measure the collective phase? I

Output configurations



- For four-photon collective phase:

$$(1,3,5,7);(2,4,6,8);\cdots \rightarrow \frac{1}{2^7}\left(1+\left|r_\sigma^{(4)}\right|\cos\phi_\sigma^{(4)}\right)$$

$$(1,3,5,8);(2,4,6,7);\cdots \rightarrow \frac{1}{2^7}\left(1-\left|r_\sigma^{(4)}\right|\cos\phi_\sigma^{(4)}\right)$$

- For pairwise overlaps, $\left|r_{(1,2)}^{(4)}\right|$ as an example:

$$(1,2,3,5);(1,2,4,5);\cdots \rightarrow \frac{1}{2^7}\left(1-r_{(1,2)}^{(4)}\right)$$

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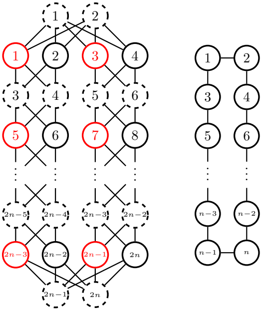
How to measure the collective phase? II

n-photon collective phase



- For n-photon collective phase:

$$\left\{ \boldsymbol{\eta} \,\middle|\, \forall i \in [n],\ \eta_i \in O^{(n)}_{\rho(i),\rho(i+1)} \right\} \to \frac{1}{2^{2n-1}} \left(1 + (-1)^{\mathrm{par}(\boldsymbol{\eta})+n} |r^{(n)}_{\sigma}| \cos \psi^{(n)}_{\sigma}\right)$$

- For pairwise overlap $r^{(n)}_{\rho(i),\rho(i+1)}$, $\binom{n-1}{n-2} 2^{n-2}$ elements in

$$\left\{ \boldsymbol{\eta} \,\middle|\, \begin{array}{l} \exists j,k \in [n], \eta_j \neq \eta_k \in O^{(n)}_{\rho(i),\rho(i+1)}; \\ \exists S \subset [n] \setminus \{\, i \,\}, |S| = n-2, \\ \forall j \in S, \exists l \in [n], \eta_l \in O^{(n)}_{\rho(j),\rho(j+1)} \end{array} \right\} \to \frac{1}{2^{2n-1}} \left(1 - r^{(n)}_{(\rho(i),\rho(i+1))}\right)$$

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Summary and Acknowledgement

Aim

Measure collective phase with shallow optical depth

Claim

$2n \times 2n$ sparse interferometry with constant optical depth, comparing with the traditional best $O(\log n)$

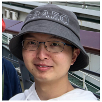
Novelty

Decrease optical depth by increasing spatial modes

Importance

Make collective phase measurement feasible

Acknowledgement



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Thank you for listening

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