Optical continuous-variable cluster states

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Teleportation “Lite”

\[ |\psi\rangle \]

\[ |+\rangle \]

\[ X^m H Z_\alpha |\psi\rangle \]

\[ m \]
Teleportation
Teleportation Network
Cluster State
Continuous-Variable Clusters

Construct CV clusters same way as for qubits
- circles: $|+_\rangle$ becomes zero-momentum eigenstate
- edges: In CV case, $C_Z = \exp(i\hat{q}_1 \otimes \hat{q}_2)$

Every CV cluster state has a corresponding graph (just as for qubits)

Optical Implementation

- 1 mode = 1 node
  - \( q = a + a^\dagger \)
  - \( p = -i(a - a^\dagger) \)

- Problem: momentum eigenstates have infinite energy (unphysical)
  - Use *finitely* squeezed vacuum states
  - Physical states \( \Rightarrow \) faulty \( \Rightarrow \) errors in computation
  - No “magic pill”—need fault tolerance from start

  \( \S \) M. Ohliger, K. Kieling, J. Eisert, arXiv:1004.0081
  \( \S \) H. Cable, D. Browne, arXiv:1008.4855

- \( C_Z \) gate can be accomplished with beam splitters and weak inline squeezing (hard!)
Measurements

- Only single-mode projective measurements are required for universal QC

- Homodyne detection (quadrature measurement) alone allows for all \textit{multimode} Gaussian operations
  - Relatively easy to do experimentally

- One non-Gaussian measurement is additionally needed for universality
  - Photon counting (harder)
Practical Preparation Method #1

- In-line squeezing ($C_Z$ gate) can be replaced with an appropriate beam splitter network*
  - In general, $O(N^2)$ optical elements needed
  - One squeezer for each mode
  - Entanglement between spatial modes

* P. van Loock, C. Weedbrook, M. Gu, PRA 76, 032321 (2007)
Practical Preparation Method #1

Advantages
- Easy to do proof-of-principle experiments now
- 4-mode CV cluster-state QC demonstrated
- Passive beamsplitters replace active $C_Z$ gates

Disadvantages
- $N$ squeezers
- Stable interferometer with $O(N^2)$ beamsplitters
- Coherence of entire state must be maintained during measurements
- $N$ is fixed for a given setup
Practical Preparation Method #2

- All squeezing and interference can be performed within a *single* crystal*
  - In general, $O(N^2)$ couplings needed
  - Single pump, single output beam
  - Entanglement between frequency modes

Single-OPO Cluster States

3 pump frequencies (polarized)
Single-OPO Cluster States

15 pump frequencies (polarized)
Single-OPO Cluster States

15 pump frequencies (polarized)

OPO
pump
cluster state
frequency-sensitive measurements

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Practical Preparation Method #2

Practical Preparation Method #2

Advantages:
- Single OPO does everything at once
- Scalability over thousands of modes
- Exactly 15 pump frequencies, regardless of size
- Nonlinear crystal already exists (PPKTP)
- Experiments underway

Disadvantages
- Finite (albeit large) scaling
- Frequency-sensitive measurements
- Coherence of entire state must be maintained during measurements
- $N$ is fixed for a given setup
- Quantum nondemolition (QND) interaction
- Information about $q$ is copied onto $p$ of other mode
- Entangling gate
- Better initial squeezing in $p$ results in more entanglement
- Hard to implement
Teleportation “Lite” Using $C_Z$ Gate
Quantum Wire Using Many $C_Z$’s
Quantum Wire Using One $C_Z$ Gate
Quantum Wire Using One $C_Z$ Gate
Quantum Wire Using One $C_Z$ Gate
Quantum Wire Using One $C_Z$ Gate
CV Cluster State Using One $C_Z$
CV Cluster State Using One $C_Z$
Temporal-Mode CV Cluster States

■ Advantages:
  • Only one squeezer, $C_Z$ gate, homodyne detector, and photon counter required
    § Just need to perfect one of each
    § Modematching and phaselocking only once
  • Grow-as-you-go
    § Robust against decoherence
    § Easy to add rows to the lattice
    § Extensible in time

■ Disadvantages
  • $C_Z$ gates are experimentally challenging
Temporal-Mode GPEPS

Diagram showing the temporal-mode GPEPS setup with labels $S_1$, $S_2$, $B_1$, $B_2$, $D_1$, and $D_2$.
Temporal-Mode GPEPS
Temporal-Mode GPEPS
Conclusion

- CV cluster states allow for measurement-based quantum computation using continuous variables

- Optical schemes
  - Squeezers + $C_Z$ gates (spatial)
  - Squeezers + beamsplitters (spatial)
  - Single OPO (frequency)
  - One squeezer + one $C_Z$ gate (temporal)
  - Four squeezers + six beamsplitters (temporal)

- Thank you