Permutationally invariant quantum tomography

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DPG Meeting, Dresden, 15 March 2011


F.Y.R.O.M. - The Former Yugoslav Republic of Macedonia
Greenland (DENMARK)
Jan Mayen (NORWAY)
Greenland Sea
Denmark Strait
Barents Sea
Norwegian Sea
Arctic Circle
Reykjavík
ICELAND
NORWAY
SWEDEN
FINLAND
RUSSIA
Hammerfest
Tromsø
Murmansk
Kiruna
White Sea
Arkhangel
Luleå
Oulu
Umeå
Trondheim
Gulf of Bothnia
Tampere
Lake Onega
Lake Ladoga
Tórshavn
Faroe Islands (DENMARK)
SHETLAND ISLANDS
ORKNEY ISLANDS
Rockall (U.K.)
HEBRIDES
Bergen
Oslo
Stavanger
Gävle
Turku
Helsinki
Gulf of Finland
St. Petersburg
Stockholm
ALAND ISLANDS
Tallinn
ESTONIA
North Atlantic Ocean
North Sea
Aberdeen
Glasgow
Edinburgh
UNITED KINGDOM
Belfast
Dublin
IRELAND
Irish Sea
Isle of Man (U.K.)
Leeds
Liverpool
Manchester
Birmingham
Cardiff
London
Celtic Sea
Göteborg
Gotland
Riga
LATVIA
Baltic Sea
DENMARK
Copenhagen
Malmö
Öland
Bornholm
LITHUANIA
Vilnius
Vitsyebsk
Smolensk
Kaliningrad
RUSSIA
Minsk
Mahilyow
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Toulouse
Milan
Venice
Turin
Genoa
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Sarajevo
Belgrade
SERBIA AND MONTENEGRO
BULGARIA
Sofia
Varna
MONACO
SAN MARINO
Florence
Andorra la Vella
ANDORRA
Marseille
Zaragoza
Porto
PORTUGAL
Madrid
Lisbon
SPAIN
Valencia
Barcelona
Balearic Sea
Ligurian Sea
Corsica
ITALY
Rome
VATICAN CITY
Adriatic Sea
Naples
Tirana
ALB.
Skopje
F.Y.R.O.M.
Thessaloníki
Istanbul
GREECE
Athens
Aegean Sea
Sardinia
Tyrrhenian Sea
BALEARIC ISLANDS
Cagliari
Ionian Sea
Sevilla
Gibraltar (U.K.)
Málaga
Strait of Gibraltar
Ceuta (SPAIN)
Alborán Sea
Melilla (SPAIN)
Oran
Algiers
Mediterranean Sea
Palermo
Sicily
Tunis
TUNISIA
Valletta
MALTA
Crete
Rabat
Casablanca
MOROCCO
ALGERIA
Scale 1: 19,500,000
Lambert Conformal Conic Projection, standard parallels 40°N and 56°N
300 Kilometers
300 Miles

BARCLAYS

Outline

1. **Motivation**
   - Why quantum tomography is important?
2. **Quantum experiments with multi-qubit systems**
   - Physical systems
   - Local measurements
   - Basic ideas and scaling
3. **Permutationally invariant tomography**
   - Main results
   - Example: XY PI tomography
   - Example: Experiment with a 4-qubit Dicke state
4. **Extra slide 1: Number of settings**

Why tomography is important?

- Many experiments aiming to create many-body entangled states.
- Quantum state tomography can be used to check how well the state has been prepared.
- However, the number of measurements scales exponentially with the number of qubits.

Outline

Physical systems

State-of-the-art in experiments

- 14 qubits with trapped cold ions
  T. Monz, P. Schindler, J.T. Barreiro, M. Chwalla, D. Nigg, W.A. Coish, M. Harlander, W. Haensel, M. Hennrich, R. Blatt, arxiv:1009.6126, 2010.

- 10 qubits with photons
  W.-B. Gao, C.-Y. Lu, X.-C. Yao, P. Xu, O. Gühne, A. Goebel, Y.-A. Chen, C.-Z. Peng, Z.-B. Chen, J.-W. Pan, Nature Physics, 6, 331 (2010).

Full tomography:

- H. Haeffner, W. Haensel, C. F. Roos, J. Benhelm, D. Chek-al-kar, M. Chwalla, T. Koerber, U. D. Rapol, M. Riebe, P. O. Schmidt, C. Becher, O. Gühne, W. Dür, R. Blatt, Nature 438, 643-646 (2005).
- N. Kiesel, C. Schmid, G. Tóth, E. Solano, and H. Weinfurter, Phys. Rev. Lett. 98, 063604 (2007).

Outline

Only local measurements are possible

Definition

A single local measurement setting is the basic unit of experimental effort.

A local setting means measuring operator $A^{(k)}$ at qubit k for all qubits.

$A^{(1)}$	$A^{(2)}$	$A^{(3)}$	...	$A^{(N)}$

- All two-qubit, three-qubit correlations, etc. can be obtained.

$$\langle A^{(1)} A^{(2)} \rangle, \langle A^{(1)} A^{(3)} \rangle, \langle A^{(1)} A^{(2)} A^{(3)} \rangle ...$$

Outline

Approaches to solve the scalability problem

Problem: the number of settings needed for full tomography increases exponentially with the number of qubits.

Possible solutions:

- If the state is expected to be of a certain form (MPS), we can measure the parameters of the ansatz.
  S.T. Flammia *et al.*, arxiv:1002.3839; M. Cramer, M.B. Plenio, arxiv:1002.3780; O. Landon-Cardinal *et al.*, arxiv:1002.4632.
- If the state is of low rank, we need fewer measurements.
  D. Gross et al., Phys. Rev. Lett. 105, 150401 (2010).
- We make tomography in a subspace of the density matrices (our approach).

Outline

Permutationally invariant part of the density matrix

Permutationally invariant part of the density matrix:

$$\varrho_{\rm PI} = \frac{1}{N!} \sum \Pi_k \varrho \Pi_k^\dagger,$$

where Π_k are all the permutations of the qubits.

- Related literature: Reconstructing $\varrho_{\rm PI}$ for spin systems.
  [G. M. D'Ariano *et al.*, J. Opt. B **5**, 77 (2003).]
- Photons in a single mode optical fiber are always in a permutationally invariant state. Small set of measurements are needed for their characterization (experiments).
  [R.B.A. Adamson *et al.*, Phys. Rev. Lett. **98**, 043601 (2007); R.B.A. Adamson *et al.*, Phys. Rev. A 2008; L. K. Shalm *et al.*, Nature **457**, 67 (2009).]

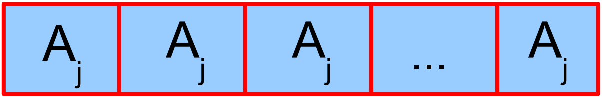
Main results

Features of our method:

1. Is for spatially separated qubits.
2. Needs the minimal number of measurement settings.
3. Uses the measurements that lead to the smallest uncertainty possible of the elements of $\varrho_{\rm PI}$.
4. Gives an uncertainty for the recovered expectation values and density matrix elements.
5. If $\varrho_{\rm PI}$ is entangled, so is ϱ. Can be used for entanglement detection!

Measurements

- We measure the same observable A_j on all qubits. (Necessary for optimality.)



- Each qubit observable is defined by the measurement directions $\vec{a}_j$ using $A_j = a_{j,x}X + a_{j,y}Y + a_{j,z}Z$.

Number of measurement settings:

$$\mathcal{D}_N = \binom{N+2}{N} = \frac{1}{2}(N^2 + 3N + 2).$$

What do we get from the measurements?

We obtain the expectation values for

$$\langle (A_j^{\otimes(N-n)} \otimes \mathbb{1}^{\otimes n})_{\mathrm{PI}} \rangle$$

for $j = 1, 2, .., \mathcal{D}_N$ and $n = 0, 1, ..., N$.

How do we obtain the Bloch vector elements?

A Bloch vector element can be obtained as

$$\underbrace{\langle (X^{\otimes k} \otimes Y^{\otimes l} \otimes Z^{\otimes m} \otimes \mathbb{1}^{\otimes n})_{\mathrm{PI}} \rangle}_{\text{Bloch vector elements}} = \sum_{j=1}^{\mathcal{D}_N} \underbrace{c_j^{(k,l,m)}}_{\text{coefficients}} \times \underbrace{\langle (A_j^{\otimes (N-n)} \otimes \mathbb{1}^{\otimes n})_{\mathrm{PI}} \rangle}_{\text{Measured data}}.$$

- Coefficients are not unique if $n > 0$.

Uncertainties

The uncertainty of the reconstructed Bloch vector element is

$$\mathcal{E}^2[(X^{\otimes k} \otimes Y^{\otimes l} \otimes Z^{\otimes m} \otimes \mathbb{1}^{\otimes n})_{\mathrm{PI}}] = \sum_{j=1}^{\mathcal{D}_N} |c_j^{(k,l,m)}|^2 \mathcal{E}^2[(A_j^{\otimes (N-n)} \otimes \mathbb{1}^{\otimes n})_{\mathrm{PI}}].$$

- For a fixed set of A_j, we have a formula to find the $c_j^{(k,l,m)}$'s giving the minimal uncertainty.

Optimization for A_j

- We have to find $\mathcal{D}_N$ measurement directions $\vec{a}_j$ on the Bloch sphere minimizing the variance

$$(\mathcal{E}_{\mathrm{total}})^2 = \sum_{k+l+m+n=N} \mathcal{E}^2\left[(X^{\otimes k} \otimes Y^{\otimes l} \otimes Z^{\otimes m} \otimes \mathbb{1}^{\otimes n})_{\mathrm{PI}}\right] \times \left(\frac{N!}{k!l!m!n!}\right).$$

Summary of algorithm

Obtaining the "total uncertainty" for given measurements

$$\left.\begin{array}{ll} \varrho_0, & \text{the state we expect} \\ A_j, & \text{what we measure} \end{array}\right\} \Rightarrow \text{BOX \#1} \Rightarrow (\mathcal{E}_{\text{total}})^2$$

Evaluating the experimental results

$$\left.\begin{array}{c} \text{measurement results} \\ A_j \end{array}\right\} \Rightarrow \text{BOX \#2} \Rightarrow \left\{\begin{array}{c} \text{Bloch vector elements} \\ \text{variances} \end{array}\right.$$

How much is the information loss?

Estimation of the fidelity $F(\varrho, \varrho_{\mathrm{PI}})$:

$$F(\varrho, \varrho_{\mathrm{PI}}) \geq \langle P_{\mathrm{s}} \rangle_{\varrho}^{2} \equiv \langle P_{\mathrm{s}} \rangle_{\varrho_{\mathrm{PI}}}^{2},$$

where P_{s} is the projector to the N-qubit symmetric subspace.

- $F(\varrho, \varrho_{\mathrm{PI}})$ can be estimated only from ϱ_{PI}!
- Proof: using the theory of angular momentum for qubits.
- Similar formalism appear concerning handling multi-copy qubit states:

  [J. I. Cirac, A. K. Ekert, C. Macchiavello, Optimal purification of single qubits PRL 1999.]

  [E. Bagan *et al.*, PRA 2006;
  G. Sentís, E. Bagan, J. Calsamiglia, R. Muñoz-Tapia, Multi-copy programmable discrimination of general qubit states, PRA 2010.]

Outline

Simple example: XY PI tomography

- Let us assume that we want to know only the expectation values of operators of the form
$$\langle A(\phi)^{\otimes N} \rangle$$
where
$$A(\phi) = \cos(\phi)\sigma_x + \sin(\phi)\sigma_y.$$

- The space of such operators has dimension $N+1$. We have to choose $\{\phi_j\}_{j=1}^{N+1}$ angles for the $\{A_j\}_{j=1}^{N+1}$ operators we have to measure.

Simple example: XY PI tomography II

- Let us assume that we measure

$$\langle A_j^{\otimes N} \rangle$$

for $j = 1, 2, ..., N+1$.

- Reconstructed values and uncertainties

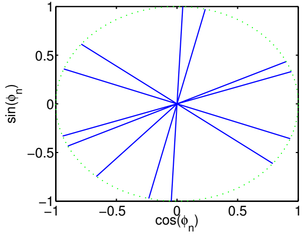
$$\underbrace{\langle A(\phi)^{\otimes N} \rangle}_{\text{Reconstructed}} = \sum_{j=1}^{N+1} \underbrace{c_j^{(\phi)}}_{\text{coefficients}} \times \underbrace{\langle A_j^{\otimes N} \rangle.}_{\text{Measured data}}$$

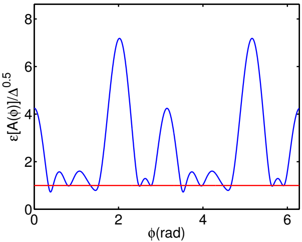
$$\mathcal{E}^2[A(\phi)] = \sum_{j=1}^{N+1} |c_j^{(\phi)}|^2 \mathcal{E}^2(A_j^{\otimes N}).$$

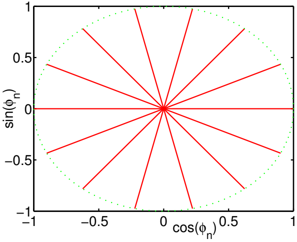
- Let us assume that all of these measurements have a variance Δ^2.

Simple example: XY PI tomography III

- Numerical example for $N = 6$.



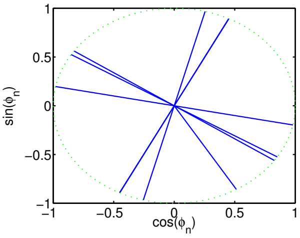




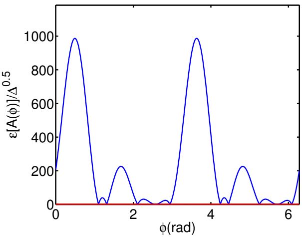
Random directions ϕ_j Uncertainty of $A(\phi)^{\otimes N}$ Uniform directions

Simple example: XY PI tomography IV

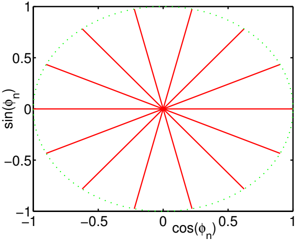
- Numerical example for $N = 6$. This random choice is even worse ...



Random directions ϕ_j



Uncertainty of $A(\phi)^{\otimes N}$



Uniform directions

Outline

4-qubit Dicke state, optimized settings (exp.)

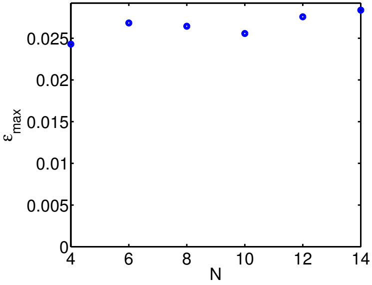
*** NEXT TALK by Christian Schwemmer ***

PI tomography for larger systems

- We determined the optimal A_j for p.i. tomography for $N = 4, 6, ..., 14$. The maximal squared uncertainty of the Bloch vector elements is

$$\epsilon_{\max}^2 = \max_{k,l,m,n} \mathcal{E}^2[(X^{\otimes k} \otimes Y^{\otimes l} \otimes Z^{\otimes m} \otimes \mathbb{1}^{\otimes n})_{\mathrm{PI}}]$$

(Total count is the same as in the experiment: 2050.)



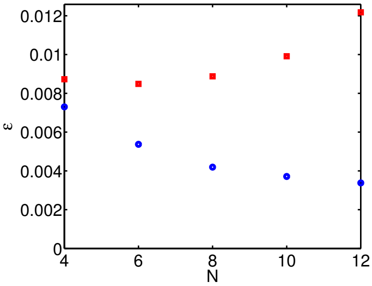
Expectation values directly from measured data

- Operator expectation values can be recovered directly from the measurement data as

$$\langle Op\rangle = \sum_{j=1}^{\mathcal{D}_N}\sum_{n=1}^{N} c_{j,n}^{Op}\langle (A_j^{\otimes(N-n)}\otimes \mathbb{1}^{\otimes n})_{\mathrm{PI}}\rangle,$$

  where the $c_{j,n}^{Op}$ are constants.

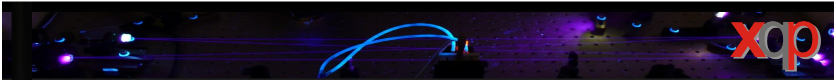
- $Op = |D_N^{(N/2)}\rangle\langle D_N^{(N/2)}|$, blue: $\varrho_0 \propto \mathbb{1}$, red: upper bound for any ϱ_0.



Comparison with other methods for efficient tomography

- If a state is detected as entangled, it is surely entangled. No assumption is used concerning the form of the quantum state.
- Expectation values of all permutationally invariant operators are the same for ϱ and $\varrho_{\rm PI}$.
- Typically, it can be used in experiments in which permutationally invariant states are created.

Participants in the project



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MPQ, Munich
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Géza Tóth
Bilbao

Summary

- We discussed permutationally invariant tomography for large multi-qubits systems.
- It paves the way for quantum experiments with more than 6 – 8 qubits.

See:

G. Tóth, W. Wieczorek, D. Gross, R. Krischek, C. Schwemmer, and H. Weinfurter, Permutationally invariant quantum tomography, Phys. Rev. Lett. 105, 250403 (2010).

THANK YOU FOR YOUR ATTENTION!

erc European Research Council

MINISTERIO DE CIENCIA E INNOVACIÓN

EUSKO JAURLARITZA GOBIERNO VASCO

How many settings we need?

- Expectation values of $(X^{\otimes k} \otimes Y^{\otimes l} \otimes Z^{\otimes m} \otimes \mathbb{1}^{\otimes n})_{\mathrm{PI}}$ are needed.
- For a given n, the dimension of this subspace is $\mathcal{D}_{(N-n)}$ (simple counting).
- Operators with different n are orthogonal to each other.
- Every measurement setting gives a single real degree of freedom for each subspace
- Hence the number of settings cannot be smaller than the largest dimension, which is $\mathcal{D}_N$.