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6. AUTHORS

5d. PROJECT NUMBER

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7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
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13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

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					19b. TELEPHONE NUMBER 886-928-1379

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RPPR Final Report
as of 21-Mar-2022

Agency Code: 21XD

Proposal Number: 72958ININT
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INVESTIGATOR(S):

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Report Date: 29-Apr-2020
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Final Report for Period Beginning 30-Jan-2019 and Ending 14-Jan-2022
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Report Term: 0-Other
Submitted By: Yueh-Nan Chen
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STEM Degrees: **STEM Participants:**

Major Goals: Our primary goal in this project is to expand the current understanding of temporal steering, and its role as a unique resource. Several years ago we introduced this new concept, identified a practical ‘temporal steering inequality’ to apply in experiments, and showed that this same inequality could be used to identify whether a channel is suitable for quantum cryptography. However, what is not yet clear is why temporal steering would be the vital resource for this type of quantum task. As well as elucidating this issue, we also plan to study what other unique features of “temporal quantum correlations” steering encapsulates, and what those features can be harnessed for. Temporal steering is a single-system temporal analogue of traditional EPR spatial steering. In EPR steering one wishes to ascertain in what way measurements done by a distant party on one part of an entangled quantum state influence the other part, held by oneself, in a way which cannot be described by classical correlations. In a similar way, temporal steering asks the question: "can correlations between measurements that were performed in the past and measurements performed in the present be described by classical physics, or are they uniquely quantum". In both cases one does not question the quantum nature of the system one has access to, but rather whether the correlations themselves are quantum in nature. Our goal in this project is to understand in what way these types of correlations are important for quantum information tasks, and what other unique applications they may have. Thus, to reiterate, our broad goals in this project are to expand our understanding of temporal steering, identify applications for this concept, and broaden interest in this exciting new concept among the wider physics research community.

Accomplishments: (1) Major activities and specific objectives

In the past three years, we focused on the following topics:
(a) Quantifying the nonclassicality of pure dephasing
(b) Demonstration of measurement-device-independent measure of quantum steering
(c) Test the non-macrorealistic cat states on quantum device.
(d) Using the steering theory to test quantum direct cause across the Cherenkov threshold.
(e) Using the spatio-temporal steering to benchmark quantum state transfer on quantum devices.
(f) Try to build a link between Bell nonlocality and the quantification of measurement incompatibility.

(2) Significant results

In the work of quantifying the nonclassicality of pure dephasing, we establish the framework of detecting and quantifying the nonclassicality for pure dephasing dynamics. The uniqueness of the canonical representation of Hamiltonian ensembles is shown, and a constructive method to determine the latter is presented.

We illustrate our method for qubit, qutrit, and qubit-pair pure dephasing and describe how to implement our approach with quantum process tomography experiments. Our work is readily applicable to present-day quantum experiments.

In the work of measurement-device-independent measure of quantum steering, we introduce a measure of steerability in an MDI scenario, i.e., the result merely depends on the observed statistics and the quantum inputs. We prove that such a measure satisfies the convex steering monotone. Moreover, it is robust against not only measurement biases but also losses. We also experimentally estimate the amount of the measure with an entangled photon source. As two by-products, our experimental results provide lower bounds on an entanglement measure of the underlying state and an incompatible measure of the involved measurement. Our research paves a way for exploring one-side deviceindependent quantum information processing within an MDI framework.

In the work of non-macrorealistic cat states on quantum device, we take advantage of the properties of the programmable nature of the IBM quantum experience to observe the violation of the Leggett–Garg inequality (in the form of a ‘quantum witness’) as a function of the number of constituent systems (qubits), while simultaneously maximizing the ‘disconnectivity’, a potential measure of macroscopicity, between constituents. Our results show that two- and four-qubit ‘cat states’ (which have large disconnectivity) are seen to violate the inequality, and hence can be classified as non-macrorealistic. In contrast, a six-qubit cat state does not violate the ‘quantum witness’ beyond a so-called clumsy invasive-measurement bound, and thus is compatible with ‘clumsy macrorealism’.

In the work of testing quantum direct cause across the Cherenkov threshold, We investigate Cherenkov radiation triggered by qubit acceleration, which can be simulated using superconducting circuits. By analyzing qubit dynamics, we confirm the existence of the Cherenkov speed threshold. We consider measurements of the quantum direct cause, which can be used to estimate channel capacity, based on a recently developed notion on temporal quantum correlations.

In the work of benchmarking quantum state transfer on quantum devices, we provide a new benchmark which reveals the nonclassicality of QST based on spatiotemporal steering (STS). We then apply the spatiotemporal steerability measurement technique to benchmark quantum devices including the IBM quantum experience and QuTech quantum inspire under QST tasks. The experimental results show that the spatiotemporal steerability decreases as the circuit depth increases, and the reduction agrees with the noise model, which refers to the accumulation of errors during the QST process. Moreover, we provide a quantity to estimate the signaling effect which could result from gate errors or intrinsic non-Markovian effect of the devices.

In the work of building a link between Bell nonlocality and the quantification of measurement incompatibility, our work includes quantifiers for both incompatible and genuine-multipartite incompatible measurements. Our method straightforwardly generalizes to include constraints on the system's dimension (semi-device-independent approach) and on projective measurements, providing improved bounds on incompatibility quantifiers, and to include the prepare-and-measure scenario.

(3) Key outcomes

We have successfully applied our theory of temporal quantum correlations in various quantum tasks. Our research findings are published in the following journals:

(A) Huan-Yu Ku, Hao-Cheng Weng, Yen-An Shih, Po-Chen Kuo, Neill Lambert, Franco Nori, Chih-Sung Chuu*, and Yueh-Nan Chen*,
Hidden nonmacrorealism: Reviving the Leggett-Garg inequality with stochastic operations
Phys. Rev. Research 3, 043083 (2021)

(B) Shin-Liang Chen, Huan-Yu Ku, Wenbin Zhou, Jordi Tura, and Yueh-Nan Chen*,
Robust self-testing of steerable quantum assemblages and its applications on device-independent quantum certification.
Quantum 5, 552 (2021).

(C) Jhen-Dong Lin, Wei-Yu Lin, Huan-Yu Ku, Neill Lambert, Yueh-Nan Chen*, and Franco Nori, Quantum steering as a witness of quantum scrambling.
Phys. Rev. A 104, 022614 (2021).

(D) Shin-Liang Chen, Nikolai Miklin, Costantino Budroni, and Yueh-Nan Chen*,
Device-independent quantification of measurement incompatibility.
Phys. Rev. Research 3, 023143 (2021).

(E) Yi-Te Huang, Jhen-Dong Lin, Huan-Yu Ku, and Yueh-Nan Chen*.
Benchmarking quantum state transfer on quantum devices.
Phys. Rev. Research 3, 023038 (2021).

(F) H.Y. Ku, N. Lambert*, F.R. Jhan, C. Emary, Y.N. Chen*, F. Nori.
Experimental test of non-macrorealistic cat-states in the cloud.
npj Quantum Information, 6, 98 (2020).

(G) Jhen-Dong Lin and Yueh-Nan Chen*.
Quantum direct cause across the Cherenkov threshold in circuit QED.
Phys. Rev. A, 102, 042223 (2020).

(H) Y. Y. Zhao, H. Y. Ku, S. L. Chen*, H. B. Chen, F. Nori, G. Y. Xiang*, C. F. Li, G. C. Guo, and Y. N. Chen*.
Experimental demonstration of measurement-device-independent measure of quantum steering.
npj Quantum Information, 6, 77 (2020).

(I) C. Y. Chu, M. H. Chou, G. Y. Chen*, and Y. N. Chen*.
Optical Quantum Frequency Filter Based on Generalized Eigenstates.
Optics Express, 28, 17868 (2020).

(J) Po-Chen Kuo, Neill Lambert, Adam Miranowicz, Hong-Bin Chen, Guang-Yin Chen, Yueh-Nan Chen*, and Franco Nori.
Collectively induced exceptional points of quantum emitters coupled to nanoparticle surface plasmons.
Physical Review A, 101, 013814 (2020).

(K) Quantifying the nonclassicality of pure dephasing,
Nature Communications 10, 3794 (2019) , Hong-Bin Chen*, Ping-Yuan Lo, Clemens Gneiting, Joonwoo Bae, Yueh-Nan Chen*, and Franco Nori.

Training Opportunities: (1) Summer workshop for open-source quantum computing software
Dates: July 29 ~ July 31 (2020)
Lecturers: Dr. Neill Lambert, Dr. Huan-Yu Ku, Mr. Jhen-Dong Lin, Mr. Yi-Te Huang.
Participants: 30

(2) Micro-course for Quantum Computing
Dates: Aug. 10 ~ Aug. 14 (2020)
Lectures: Prof. Yueh-Nan Chen, Prof. Tse-Ming Chen, Mr. Guan-Ting Chen.
Participants: 23

(3) Micro-course for Quantum Computing Dates: Aug. 14 ~ Aug. 15 (2021)
Lectures: Prof. Yueh-Nan Chen, Dr. Huan-Yu Ku, Mr. Guan-Ting Chen, Mr. Jheng-Dong Lin, and Yi-Te Huang.
Participants: 30.

Results Dissemination: (1) Reports by NCKU News Center
http://news.secr.ncku.edu.tw/p/406-1037-210896,r81.php
http://news.secr.ncku.edu.tw/p/405-1037-210877,c595.php

(2) News in Commercial Times:
https://ctee.com.tw/industrynews/cooperation/475902.html

(3) Invited article of popular science on quantum computing, published by Science Monthly.
https://www.scimonth.com.tw/archives/5160

Honors and Awards: (1) Awarded as Center Scientist of National Center for Theoretical Sciences (Taiwan)

(2) A new center was founded in July of 2020 at NCKU: Center for Quantum Frontiers of Research &Technology (QFort)

(3) CTCI Outstanding Physics Research Award (2020)

(4) MOST Outstanding Research Award (2021)

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Hong-Bin Chen
Person Months Worked: 8.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Co PD/PI
Participant: Franco Nori
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Co PD/PI
Participant: Neill Lambert
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Co PD/PI
Participant: Adam Miranowicz
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Huan-Yu Ku
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Shin-Liang Chen
Person Months Worked: 12.00 **Funding Support:**

Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Guang-Ting Chen
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Po-Chen Kuo
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Jhen-Dong Lin
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Fong-Ruei Jhan
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Co PD/PI
Participant: Clemens Gneiting
Person Months Worked: 1.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Yi-Te Huang
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

International Collaboration:

USA

JPN

POL

ARTICLES:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review A
Publication Identifier Type: DOI Publication Identifier:
Volume: 101 Issue: First Page #: 013814
Date Submitted: Date Published: 1/13/20 8:00AM
Publication Location: New York
Article Title: Collectively induced exceptional points of quantum emitters coupled to nanoparticle surface plasmons
Authors: Po-Chen Kuo, Neill Lambert, Adam Miranowicz, Hong-Bin Chen, Guang-Yin Chen, Yueh-Nan Chen&#x
Keywords: quantum dots, plasmons, exceptional points
Abstract: Exceptional points, resulting from non-Hermitian degeneracies, have the potential to enhance the capabilities of quantum sensing. Thus, finding exceptional points in different quantum systems is vital for developing such future sensing devices. Taking advantage of the enhanced light-matter interactions in a confined volume on a metal nanoparticle surface, here we theoretically demonstrate the existence of exceptional points in a system consisting of quantum emitters coupled to a metal nanoparticle of subwavelength scale. By using an analytical quantum electrodynamics approach, exceptional points are manifested as a result of a strong-coupling effect and observable in a drastic splitting of originally coalescent eigenenergies. Furthermore, we show that exceptional points can also occur when a number of quantum emitters are collectively coupled to the dipole mode of localized surface plasmons.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Partners

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RPPR Final Report
as of 21-Mar-2022

I certify that the information in the report is complete and accurate:
Signature: Yueh-Nan Chen
Signature Date: 3/13/22 11:49PM

Temporal Quantum Steering (Final Report 2022)

PI: Prof. Yueh-Nan Chen
Department of Physics
Center for Quantum Frontiers of Research & Technology
National Cheng Kung University, Tainan, Taiwan.

1. How many peer-reviewed publications resulted from the Grant?

   Twelve manuscripts are published from the Grant.

   (Nat. Commun., npj Quantum Information, Phys. Rev. A, Sci. Rep., Phys. Rev. Research, Quantum).

2. How many manuscripts (unpublished) resulted from the Grant? (These are just numbers.)

   Two manuscripts under review.

3. How many graduate students and postdocs received support from this Grant (average per year)?

   Five Phd students and three postdocs.

4. What PI awards or honors (if any) have you received?

   Received two awards: CTCI Outstanding Physics Research Award (2020)

   MOST Outstanding Research Award (2021)

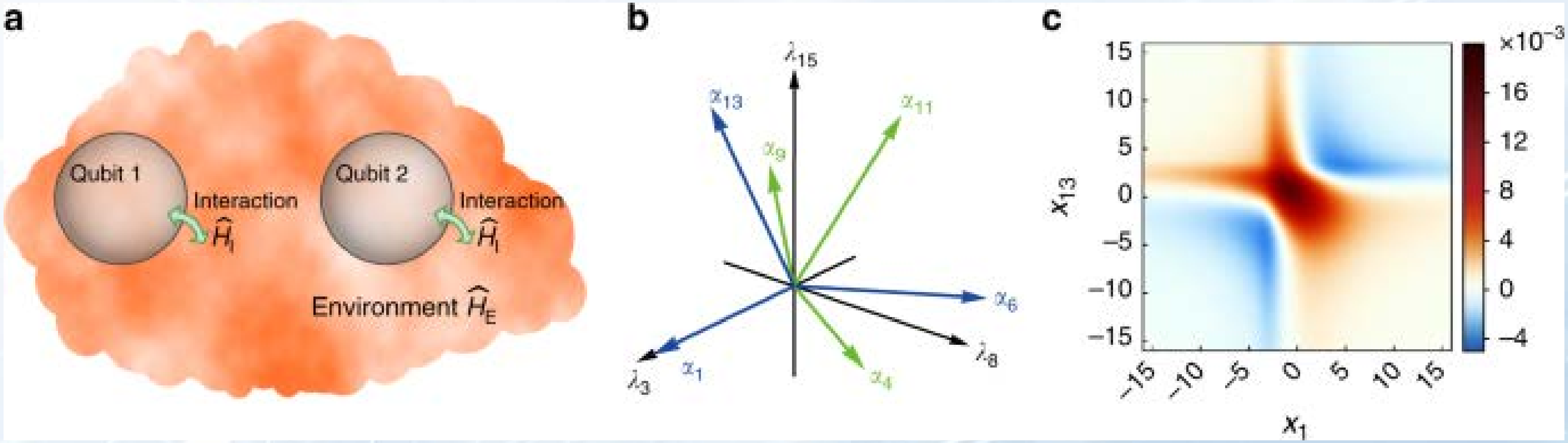
5. What are your best technical accomplishments that the Grant supported? Please provide a few text bullets.

   We propose a theory to quantify the nonclassicality of pure dephasing and the results are published in Nat. Commun.

Two Major Awards

Major publications under the support of the Grant

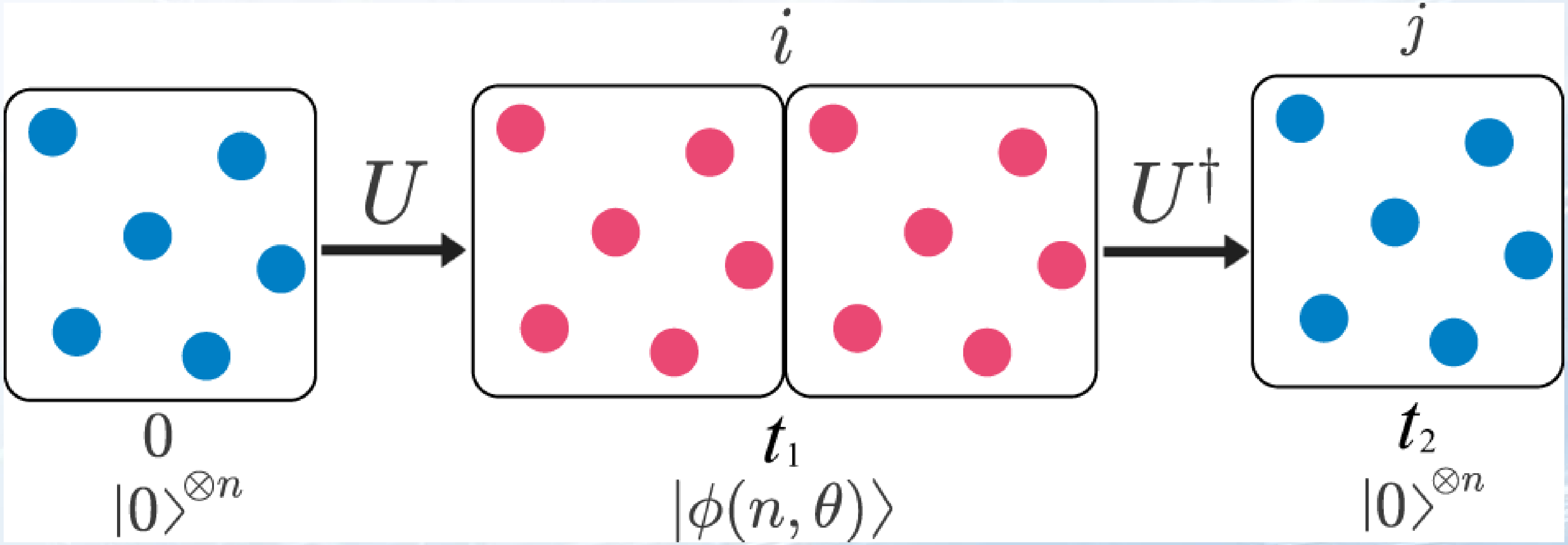
Quantifying the nonclassicalty of pure dephasing
[Nat. Commun. 10, 3794 (2019)]



Nonclassicality of the qubit pair pure dephasing.

Experimental test of non-macrorealistic cat states in the cloud

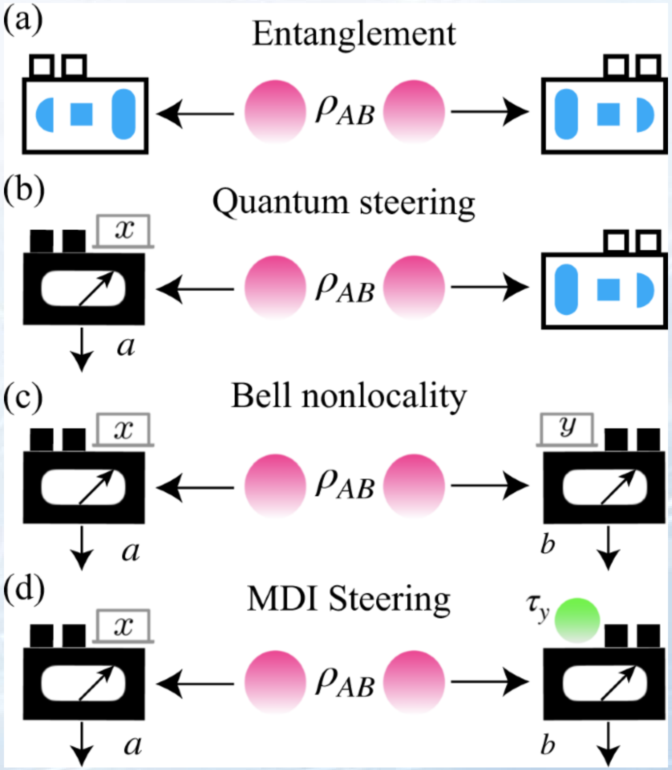
[npj Quantum Information 6, 98 (2020)]



Schematic setup to observe the violation of the Leggett–Garg inequality (in the form of a ‘quantum witness’).

Experimental demonstration of measurement-device-independent measure of quantum steering

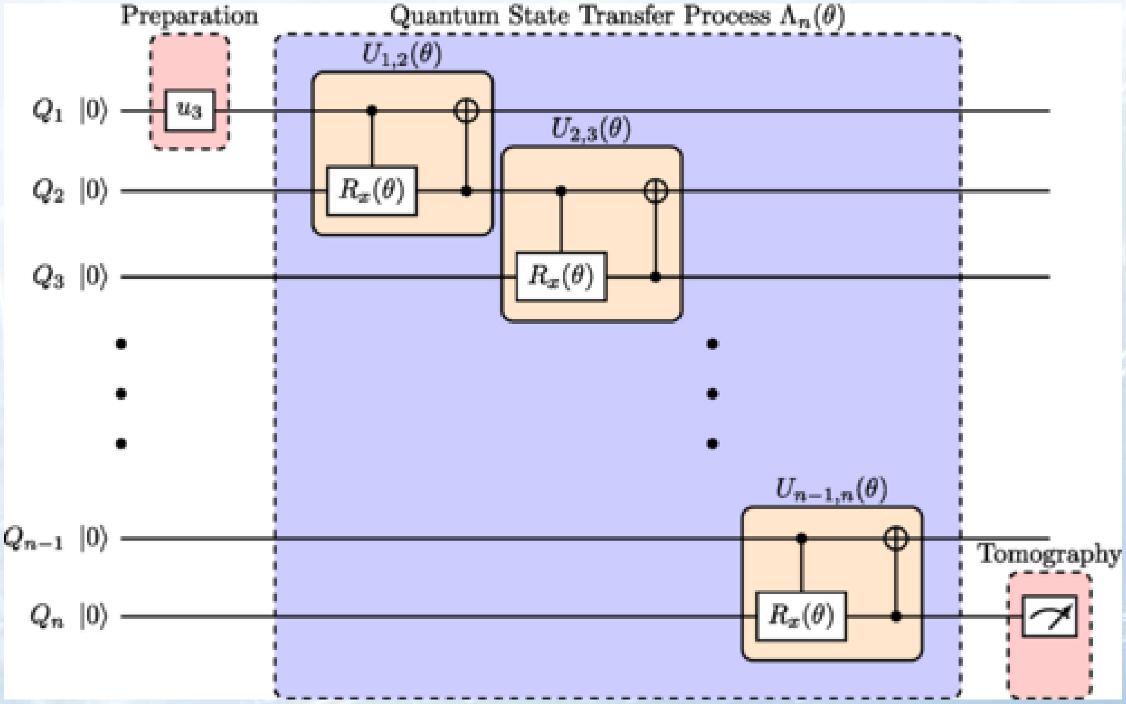
[npj Quantum Information 6, 77 (2020)]



A pair of entangled photons ρ_{AB} (pink balls) are shared between two spatially separated parties: Alice and Bob. They verify whether they share the entanglement, steering, and nonlocal resource.

Benchmarking quantum state transfer on quantum devices

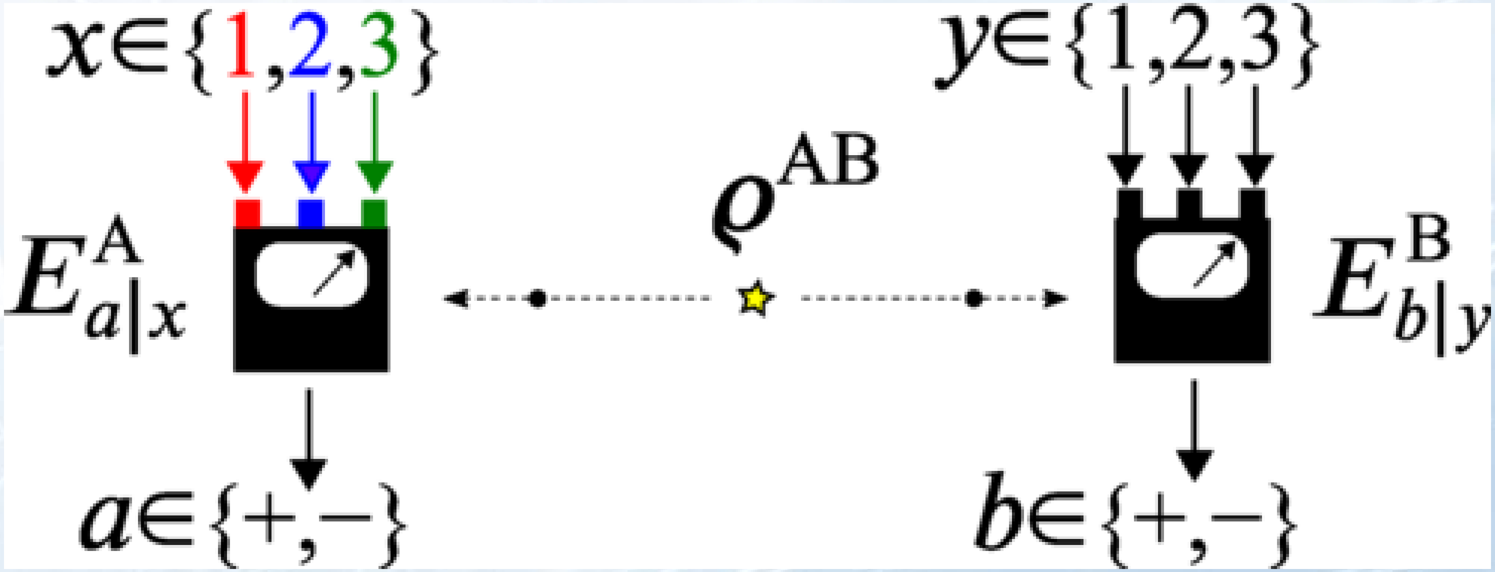
[Phys. Rev. Research **3**, 023038 (2021)]



Circuit implementation of quantum state transfer.

Device-independent quantification of measurement incompatibility

[Phys. Rev. Research **3**, 023143 (2021)]



Schematic representation of device-independent quantification of measurement incompatibility.