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1. REPORT DATE (DD-MM-YYYY) 06-09-2023	2. REPORT TYPE Final Report	3. DATES COVERED (From - To) 1-Oct-2013 - 30-Sep-2016
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4. TITLE AND SUBTITLE Advanced Quantum Sensing	5a. CONTRACT NUMBER W911NF-13-1-0402
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 611102

6. AUTHORS Paul Kwiat, Andrew Jordan, Courtney Byard	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES University of Illinois - Urbana - Champaign c/o Office of Sponsored Programs 1901 S. First Street, Suite A Champaign, IL 61820 -7406	8. PERFORMING ORGANIZATION REPORT NUMBER
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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES) U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSOR/MONITOR'S ACRONYM(S) ARO
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) 63986-PE.20

12. DISTRIBUTION AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.
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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 be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT Over the past year, we have been continuing to work toward demonstrating an SNR improvement with our multi-pass system. Our current implementation allows for an SNR improvement by a factor of 2.5, potentially improvable to around 3. We have also worked to perform a proof-of-principle demonstration of the quantum Zeno effect, based on spatial mode filtering. On the theory side, we have shown that with biphotons we can beat the uncorrelated photon case in term of precision using the tight position/momentum correlations, that weak value amplification gives a fundamental advantage in suppressing systematic errors on the meter, and that with a time dependent

15. SUBJECT TERMS Weak measurements, quantum metrology

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Paul Kwiat
a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU			19b. TELEPHONE NUMBER 217-333-9116

RPPR Final Report
as of 19-Sep-2023

Agency Code: 21XD

Proposal Number: 63986PE

Agreement Number: W911NF-13-1-0402

INVESTIGATOR(S):

Name: Paul Kwiat Ph.D.
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Principal: Y

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Country: USA

DUNS Number: 041544081

EIN: 376000511

Report Date: 31-Oct-2014

Date Received: 06-Sep-2023

Final Report for Period Beginning 01-Oct-2013 and Ending 30-Sep-2016

Title: Advanced Quantum Sensing

Begin Performance Period: 01-Oct-2013

End Performance Period: 30-Apr-2019

Report Term: 0-Other

Submitted By: Paul Kwiat

Email: kwiat@illinois.edu

Phone: (217) 333-9116

Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 4

STEM Participants: 5

Major Goals: Quantum weak measurement are known to enable amplification of weak signals, and particularly show an advantage in the presence of many types of systematic noise (which is relatively de-amplified by the process). Despite the arbitrarily large weak value, any amplification is necessarily accompanied by a corresponding decrease in the number of statistics (due to the post-selection), i.e., the increase in signal is canceled by an equal increase in noise. To combat this effect, we have proposed both discrete and continuous methods for recycling the light typically lost from post-selection, so most of the initial intensity is eventually detected. Specifically, we want to redirect unused photons back through the system for repeated attempts at weak measurement. In this way, every photon is in principle eventually detected. Because, for a shot-noise limited measurement, the signal-to-noise ratio (SNR) is proportional to the square root of the number of photons incident on the detector, we showed that collecting a larger portion of the incident light should increase the SNR substantially. Our primary goal is to demonstrate this enhancement by implementing our proposed discrete and continuous recycling schemes. We have also shown theoretically that using entangled photons can lead to additional gains in sensitivity; implementing such a scheme is an additional goal of this research. Finally, we aim to understand more broadly when such schemes can be used to enhance various metrological applications, from atomic force microscopy to estimating the parameters of a Hamiltonian.

This project also received supplemental funding to further research on the use of time-multiplexing to improve single-photon sources and quantum communication applications relying on synchronous arrival of multiple independent photons. The goal is to demonstrate the large advantage achievable through the use of multiplexing techniques, particularly when implemented using an ultra-low loss quantum memory.

Accomplishments: See Attachment.

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Training Opportunities: Six students worked on this project over its duration, three graduate students, two undergraduates, and one high school student (the latter as part of a summer program to foster research interest in underrepresented students). These students all received various training opportunities. At a basic level, they were mentored in proper research techniques, as well as in appropriate presentation skills. For example, one of the undergraduates learned how to measure the coherence length of very narrow linewidth lasers, as well as how to construct and optimize novel interferometers. The graduate students presented their results at national and international conferences, gaining valuable feedback from their peers. The senior graduate students were also mentored in Professional Development, with discussions about long-term career trajectories, and the best way to achieve the student's long-term career goals. Graduate students Kevin Lyons, Courtney Krafczyk and Areeya Chantasri, all supported by this grant, finished their Ph. D.s and graduated. The graduate students were also in charge of mentoring the undergraduate and high school students (and received guidance in the best way to do that). The project also partially supported three postdoctoral researchers; in addition to mentorship on how to address 'the big picture' in research, they also received mentoring on the best way to pursue their future long-term goals (beyond a postdoctoral position); the two UIUC postdocs now have university faculty positions, in Japan.

Results Dissemination: Our research results were disseminated via numerous publications, as well as presentations at a number of conferences, and seminars and colloquia given at various universities. These presentations were given by both the PIs and the students working on the project. In terms of Outreach, the Illinois group undertook a rather unique science outreach activity (with minor support from the American Physical Society): we set up LabEscape, the world's first science-puzzle-based 'Escape Game', based on the increasingly popular Escape Rooms, but using puzzles that are mostly based on physics. In playing the game, participants are exposed to a number of physics concepts (e.g., how a laser works, what is polarization and how is it used, how does magnetic induction work, etc.), and how these are relevant in their daily lives. The PI (Kwiat), graduate student (Krafczyk), and undergraduate (Call) volunteered time to push this project forward. The room opened at a local mall in 2016 (though the official Grand Opening was in January 2017), and ran until we closed due to COVID in 2020; we have subsequently reopened in a building on campus. Thus far we have run over 10,000 participants (and probably exposed about 3 times that number to interesting physics phenomena at various summer fairs, farmer's markets, etc.); we received over 98% 5-star ratings, with 98% of survey respondents saying they would recommend LabEscape to friends or family, and 87% saying they had discovered something new about science as a result of the experience. The other relevant aspect is that many of our science puzzles were created by undergraduates, under the supervision of the PI. For more information, see LabEscape.org.

Honors and Awards: "Article of the Year" for the journal, Quantum Studies: Mathematics and Foundations, for Jordan, A.N., Tollaksen, J., Troupe, J.E. et al. Quantum Stud.: Math. Found. (2015) 2: 5. doi:10.1007/s40509-015-0036-8

Editor's suggestion for a joint publication in PRA:
Phys. Rev. A 93, 043841 (2016)

PI Paul Kwiat received the Optical Society of America 2017 James P. Gordon Speakership.

Co-PI Andrew Jordan received a Simons Fellowship in Theoretical Physics, which he is applied to his 2017/2018 sabbatical leave.

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Faculty

Participant: Paul Kwiat

Person Months Worked: 2.00

Project Contribution:

National Academy Member: N

Funding Support:

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Participant Type: Faculty
Participant: Andrew Jordan
Person Months Worked: 2.00
Project Contribution:
National Academy Member: N
Funding Support:

Participant Type: Graduate Student (research assistant)
Participant: Courtney Krafczyk
Person Months Worked: 12.00
Project Contribution:
National Academy Member: N
Funding Support:

Participant Type: Graduate Student (research assistant)
Participant: Kevin Lyons
Person Months Worked: 12.00
Project Contribution:
National Academy Member: N
Funding Support:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Shengshi Pang
Person Months Worked: 6.00
Project Contribution:
National Academy Member: N
Funding Support:

Participant Type: Graduate Student (research assistant)
Participant: Areeya Chantasri
Person Months Worked: 12.00
Project Contribution:
National Academy Member: N
Funding Support:

Participant Type: High School Student
Participant: Davon Minor
Person Months Worked: 2.00
Project Contribution:
National Academy Member: N
Funding Support:

Participant Type: Undergraduate Student
Participant: Ian Call
Person Months Worked: 4.00
Project Contribution:
National Academy Member: N
Funding Support:

Participant Type: Undergraduate Student
Participant: Julia Spina

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Person Months Worked: 5.00
Project Contribution:
National Academy Member: N

Funding Support:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Soyoung Baek

Person Months Worked: 4.00

Funding Support:

Project Contribution:

National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)

Participant: Fumihiko Kaneda

Person Months Worked: 10.00

Funding Support:

Project Contribution:

National Academy Member: N

ARTICLES:

Publication Type: Journal Article

Peer Reviewed: Y

Publication Status: 1-Published

Journal: Physical Review X

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevX.4.011031

Volume: 4 Issue: 1

First Page #: 11031

Date Submitted:

Date Published:

Publication Location:

Article Title: Technical Advantages for Weak-Value Amplification: When Less Is More

Authors:

Keywords: Weak measurements, precision metrology

Abstract: The technical merits of weak-value-amplification techniques are analyzed. We consider models of several different types of technical noise in an optical context and show that weak-value-amplification techniques (which only use a small fraction of the photons) compare favorably with standard techniques (which use all of them). Using the Fisher-information metric, we demonstrate that weak-value techniques can put all of the Fisher information about the detected parameter into a small portion of the events and show how this fact alone gives technical advantages. We go on to consider a time-correlated noise model and find that a Fisher-information analysis indicates that the standard method can have much larger information about the detected parameter than the postselected technique. However, the estimator needed to gather the information is technically difficult to implement, showing that the inefficient (but practical) signal-to-noise estimation of the parameter is usually superior. We a

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors

Acknowledged Federal Support:

RPPR Final Report as of 19-Sep-2023

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Reviews of Modern Physics
Publication Identifier Type: DOI **Publication Identifier:** 10.1103/RevModPhys.86.307
Volume: 86 **Issue:** 1 **First Page #:** 307
Date Submitted: 10/19/17 12:00AM **Date Published:** 3/28/14 5:00AM
Publication Location:

Article Title: Understanding quantum weak values: Basics and applications

Authors: Justin Dressel, Mehul Malik, Filippo M. Miatto, Andrew N. Jordan, and Robert W. Boyd

Keywords: quantum weak measurements, tutorial, precision measurement

Abstract: Since its introduction 25 years ago, the quantum weak value has gradually transitioned from a theoretical curiosity to a practical laboratory tool. While its utility is apparent in the recent explosion of weak value experiments, its interpretation has historically been a subject of confusion. Here a pragmatic introduction to the weak value in terms of measurable quantities is presented, along with an explanation for how it can be determined in the laboratory. Further, its application to three distinct experimental techniques is reviewed. First, as a large interaction parameter it can amplify small signals above technical background noise. Second, as a measurable complex value it enables novel techniques for direct quantum state and geometric phase determination. Third, as a conditioned average of generalized observable eigenvalues it provides a measurable window into nonclassical features of quantum mechanics. In this selective review, a single experimental configuration to discuss and

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors

Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Quantum Studies: Mathematics and Foundations
Publication Identifier Type: DOI **Publication Identifier:** 10.1007/s40509-015-0044-8
Volume: 2.0E+000 **Issue:** 3.0E+000 **First Page #:** 255
Date Submitted: **Date Published:**
Publication Location:

Article Title: Can a Dove prism change the past of a single photon?

Authors:

Keywords: Weak values, interpretation

Abstract: We reexamine the thought experiment and real experiment of Danan et al. (Phys Rev Lett 111:240402, 2013), Vaidman (Phys Rev A 89:024102, 2014), Vaidman (Phys Rev A 87:052104, 2013), by placing Dove prisms in the nested Mach–Zehnder interferometer arms. In those previous works, the criterion of whether a single photon was present, or not, was the presence of a “weak trace,” indicating the presence of a nonzero weak value. This “weak trace” was tested by slightly varying the mirror angle at a given frequency, and then verifying whether this variation led to a signal at the corresponding frequency on a position-sensitive detector. We show that the presence of the Dove prisms gives identical weak values everywhere to the previous configuration because the prisms change neither the path difference, nor the mode profile in the aligned case. Nevertheless, the same slight variations of the interferometer mirrors now give a signal at the first mirror of the nested interferometer, indicating the

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Acknowledged Federal Support:

RPPR Final Report as of 19-Sep-2023

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI **Publication Identifier:** 10.1103/PhysRevLett.114.170801
Volume: 1.14E+002 **Issue:** 1.7E+001 **First Page #:** 170801
Date Submitted: **Date Published:**
Publication Location:

Article Title: Power-Recycled Weak-Value-Based Metrology

Authors:

Keywords: Weak measurements, power recycling

Abstract: We improve the precision of the interferometric weak-value-based beam deflection measurement by introducing a power recycling mirror, creating a resonant cavity. This results in all the light exiting to the detector with a large deflection, thus eliminating the inefficiency of the rare postselection. The signal-to-noise ratio of the deflection is itself magnified by the weak value. We discuss ways to realize this proposal, using a transverse beam filter and different cavity designs.

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Quantum Studies: Mathematics and Foundations
Publication Identifier Type: DOI **Publication Identifier:** 10.1007/s40509-015-0036-8
Volume: 2.0E+000 **Issue:** 1.0E+000 **First Page #:** 5
Date Submitted: **Date Published:**
Publication Location:

Article Title: Heisenberg scaling with weak measurement: a quantum state discrimination point of view

Authors:

Keywords: Quantum weak measurements

Abstract: We examine the results of the paper "Precision metrology using weak measurements" (Zhang et al. arXiv:1310.7530, 2013) from a quantum state discrimination point of view. The Heisenberg scaling of the photon number for the precision of the interaction parameter between coherent light and a spin one-half particle (or pseudo-spin) has a simple interpretation in terms of the interaction rotating the quantum state to an orthogonal one. To achieve this scaling, the information must be extracted from the spin rather than from the coherent state of light, limiting the applications of the method to phenomena such as cross-phase modulation. We next investigate the effect of dephasing noise and show a rapid degradation of precision, in agreement with general results in the literature concerning Heisenberg scaling metrology. We also demonstrate that a von Neumann-type measurement interaction can display a similar effect with no system/meter entanglement.

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support:

RPPR Final Report

as of 19-Sep-2023

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: submitted to Phys. Rev. A
Publication Identifier Type: Other **Publication Identifier:** arXiv:1606.01407v1
Volume: **Issue:** **First Page #:**
Date Submitted: 10/19/17 12:00AM **Date Published:** 8/31/16 10:47AM
Publication Location:

Article Title: Rapid estimation of drifting parameters in continuously measured quantum systems

Authors: Luis Cortez, Areeya Chantasri, Luis Pedro García-Pintos, Justin Dressel, Andrew N. Jordan

Keywords: continuous measurement, Hamiltonian parameter estimation

Abstract: We investigate the determination of a Hamiltonian parameter in a quantum system undergoing continuous measurement. We demonstrate a computationally rapid yet statistically optimal method to estimate an unknown and possibly time-dependent parameter, where we maximize the likelihood of the observed stochastic readout. By dealing directly with the raw measurement record rather than the quantum state trajectories, the estimation can be performed while the data is being acquired, permitting continuous tracking of the parameter during slow drifts in real time. Furthermore, we incorporate realistic nonidealities, such as decoherence processes and measurement inefficiency. As an example, we focus on estimating the value of the Rabi frequency of a continuously measured qubit, and compare maximum likelihood estimation to a simpler fast Fourier transform. Using this example, we discuss how the quality of the estimation depends on both the strength and duration of the measurement.

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Quantum Studies: Mathematics and Foundations
Publication Identifier Type: DOI **Publication Identifier:** 10.1007/s40509-016-0075-9
Volume: 3 **Issue:** 3 **First Page #:** 237
Date Submitted: 8/30/16 12:00AM **Date Published:** 5/1/16 10:00AM
Publication Location:

Article Title: Anatomy of fluorescence: quantum trajectory statistics from continuously measuring spontaneous emission

Authors: Andrew N. Jordan, Areeya Chantasri, Pierre Rouchon, Benjamin Huard

Keywords: Quantum trajectories, quantum measurement, Spontaneous emission, Heterodyne measurement, Stochastic path integral

Abstract: We investigate the continuous quantum measurement of a superconducting qubit undergoing fluorescence. The fluorescence of the qubit is detected via a phase preserving heterodyne measurement, giving the fluorescence quadrature signals as two continuous qubit readout results. Using the stochastic path integral approach to the measurement physics, we derive most likely paths between boundary conditions on the state, and compute approximate time correlation functions between all stochastic variables via diagrammatic perturbation theory. We focus on paths that increase in energy during the continuous measurement. Our results are compared to Monte Carlo numerical simulation of the trajectories, and we find close agreement between direct simulation and theory. We generalize this analysis to arbitrary diffusive quantum systems that are continuously monitored.

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: Y

RPPR Final Report as of 19-Sep-2023

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Physical Review A

Publication Identifier Type: DOI

Publication Identifier: 10.1103/PhysRevA.96.020301

Volume: 96

Issue: 2

First Page #: 020301

Date Submitted: 10/19/17 12:00AM

Date Published: 8/1/17 10:00AM

Publication Location:

Article Title: Quantum parameter estimation with the Landau-Zener transition

Authors: Jing Yang, Shengshi Pang, Andrew N. Jordan

Keywords: quantum parameter estimation, quantum Fisher information

Abstract: We investigate the fundamental limits in precision allowed by quantum mechanics from Landau-Zener transitions, concerning Hamiltonian parameters. While the Landau-Zener transition probabilities depend sensitively on the system parameters, much more precision may be obtained using the acquired phase, quantified by the quantum Fisher information. This information scales with a power of the elapsed time for the quantum case, whereas it is time independent if the transition probabilities alone are used. We add coherent control to the system and increase the permitted maximum precision in this time-dependent quantum system. The case of multiple passes before measurement, Landau-Zener-Stueckelberg interferometry, is considered, and we demonstrate that proper quantum control can cause the quantum Fisher information about the oscillation frequency to scale as T^4 , where T is the elapsed time. These results are foundational for frequency standards and quantum clocks.

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors

Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Nature Communications

Publication Identifier Type: DOI

Publication Identifier: 10.1038/ncomms14695

Volume: 8

Issue:

First Page #: 14695

Date Submitted: 10/19/17 12:00AM

Date Published: 3/1/17 6:00AM

Publication Location:

Article Title: Optimal adaptive control for quantum metrology with time-dependent Hamiltonians

Authors: Shengshi Pang, Andrew N. Jordan

Keywords: quantum metrology, optimal control

Abstract: Quantum metrology has been studied for a wide range of systems with time-independent Hamiltonians. For systems with time-dependent Hamiltonians, however, due to the complexity of dynamics, little has been known about quantum metrology. Here we investigate quantum metrology with time-dependent Hamiltonians to bridge this gap. We obtain the optimal quantum Fisher information for parameters in time-dependent Hamiltonians, and show proper Hamiltonian control is generally necessary to optimize the Fisher information. We derive the optimal Hamiltonian control, which is generally adaptive, and the measurement scheme to attain the optimal Fisher information. In a minimal example of a qubit in a rotating magnetic field, we find a surprising result that the fundamental limit of T^2 time scaling of quantum Fisher information can be broken with time-dependent Hamiltonians, which reaches T^4 in estimating the rotation frequency of the field.

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors

Acknowledged Federal Support: Y

RPPR Final Report as of 19-Sep-2023

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Optica

Publication Identifier Type: DOI

Publication Identifier: 10.1364/OPTICA.4.001034

Volume: 4

Issue: 9

First Page #: 1034

Date Submitted: 10/19/17 12:00AM

Date Published: 8/1/17 5:00AM

Publication Location:

Article Title: Quantum-memory-assisted multi-photon generation for efficient quantum information processing

Authors: Fumihiro Kaneda, Feihu Xu, Joseph Chapman, Paul G. Kwiat

Keywords: optical memory, measurement-device-independent quantum key distribution, synchronization

Abstract: Efficient preparation of large, but definite, numbers of photons is of great importance for scaling up and speeding up photonic quantum information processing. Typical single-photon generation techniques based on nonlinear parametric processes face challenges of probabilistic generation. Here we demonstrate efficient synchronization of photons from multiple nonlinear parametric heralded single-photon sources, using quantum memories. Our low-loss optical memories greatly enhance ($\sim 30\times$) the generation rate of coincidence photons from two independent sources, while maintaining high indistinguishability ($95.7\pm 1.4\%$) of the synchronized photons. As an application, we perform the first demonstration of parametric-source-based measurement-device-independent quantum key distribution. The synchronization technique demonstrated here paves the way toward efficient quantum communication and larger-scale optical quantum computing.

Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors

Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Physical Review Letters

Publication Identifier Type: DOI

Publication Identifier: 10.1103/physrevlett.119.220507

Volume: 119

Issue: 22

First Page #: 220507

Date Submitted: 9/6/23 12:00AM

Date Published: 12/1/17 6:00AM

Publication Location:

Article Title: Arrow of Time for Continuous Quantum Measurement

Authors: Justin Dressel, Areeya Chantasri, Andrew N. Jordan, Alexander N. Korotkov,

Keywords: General Physics and Astronomy

Abstract: We investigate the statistical arrow of time for a quantum system being monitored by a sequence of measurements. For a continuous qubit measurement example, we demonstrate that time-reversed evolution is always physically possible, provided that the measurement record is also negated. Despite this restoration of dynamical reversibility, a statistical arrow of time emerges, and may be quantified by the log-likelihood difference between forward and backward propagation hypotheses. We then show that such reversibility is a universal feature of nonprojective measurements, with forward or backward Janus measurement sequences that are time-reversed inverses of each other.

Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info

Acknowledged Federal Support: Y

RPPR Final Report as of 19-Sep-2023

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Quantum Studies: Mathematics and Foundations

Publication Identifier Type: DOI

Publication Identifier: 10.1007/s40509-017-0145-7

Volume: 5

Issue: 4

First Page #: 579

Date Submitted: 9/6/23 12:00AM

Date Published: 10/26/17 5:00AM

Publication Location:

Article Title: Noise suppression in inverse weak value-based phase detection

Authors: Kevin Lyons, John C. Howell, Andrew N. Jordan,

Keywords: Mathematical Physics

Abstract: We examine the effect of different sources of technical noise on inverse weak value-based precision phase measurements. We find that this type of measurement is similarly robust to technical noise as related experiments in the weak value regime. In particular, the measurements considered here are robust to additive Gaussian white noise and angular jitter noise commonly encountered in optical experiments. Additionally, we show the same techniques used for precision phase measurement can be used with the same technical advantages for optical frequency measurements.

Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info

Acknowledged Federal Support: Y

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published

Journal: Physical Review Letters

Publication Identifier Type: DOI

Publication Identifier: 10.1103/physrevlett.126.220801

Volume: 126

Issue: 22

First Page #:

Date Submitted: 9/6/23 12:00AM

Date Published: 6/1/21 5:00AM

Publication Location:

Article Title: Enhanced Weak-Value Amplification via Photon Recycling

Authors: Courtney Krafczyk, Andrew N. Jordan, Michael E. Goggin, Paul G. Kwiat,

Keywords: General Physics and Astronomy

Abstract: In a quantum-noise limited system, weak-value amplification using postselection normally does not produce more sensitive measurements than standard methods for ideal detectors: the increased weak value is compensated by the reduced power due to the small postselection probability. Here, we experimentally demonstrate recycled weak-value measurements using a pulsed light source and optical switch to enable nearly deterministic weak-value amplification of a mirror tilt. Using photon counting detectors, we demonstrate a signal improvement by a factor of 4.4 ± 0.2 and a signal-to-noise ratio improvement of 2.10 ± 0.06 , compared to a single-pass weak-value experiment, and also compared to a conventional direct measurement of the tilt. The signal-to-noise ratio improvement could reach around six for the parameters of this experiment, assuming lower loss elements.

Distribution Statement: 1-Approved for public release; distribution is unlimited.

Acknowledged Federal Support: Y

RPPR Final Report
as of 19-Sep-2023

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: CLEO: QELS_Fundamental Science
Date Received: 19-Oct-2017 Conference Date: 15-May-2017 Date Published: 15-May-2017
Conference Location: San Jose, California
Paper Title: Relative time multiplexing of heralded single photons for efficient quantum communication
Authors: Fumihiro Kaneda, Alexander Hill, and Paul G. Kwiat
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: CLEO: Applications and Technology
Date Received: 19-Oct-2017 Conference Date: 15-May-2017 Date Published: 15-May-2017
Conference Location: San Jose, California
Paper Title: Synchronized Spontaneous Downconversion Supplies Scalable Single-Photon Sources
Authors: P. G. Kwiat, F. Kaneda, F. Bergmann, M. Victoria
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 3-Accepted
Conference Name: Frontiers in Optics
Date Received: 19-Oct-2017 Conference Date: 17-Oct-2016 Date Published: 17-Oct-2016
Conference Location: Rochester, New York
Paper Title: Weak Value Measurements with Pulse Recycling
Authors: Courtney Byard, Trent Graham, Andrew Jordan, and Paul Kwiat
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Frontiers in Optics
Date Received: 19-Oct-2017 Conference Date: 18-Oct-2015 Date Published:
Conference Location: San Jose, California
Paper Title: Pulse Recycling and Weak Value Metrology
Authors: Courtney Byard, Trent Graham, Andrew Jordan, and Paul G. Kwiat
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: APS March meeting
Date Received: 20-Oct-2017 Conference Date: 13-Mar-2017 Date Published: 13-Mar-2017
Conference Location: New Orleans, Louisiana
Paper Title: Suppressing systematic errors in weak measurements
Authors: Shengshi Pang, Jose Raul Gonzalez Alonso, Todd A. Brun, Andrew N. Jordan
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: QCrypt
Date Received: 20-Oct-2017 Conference Date: 24-Oct-2016 Date Published: 24-Oct-2016
Conference Location: Washington, DC
Paper Title: Synchronized Heralded Single Photons
Authors: Fumihiro Kaneda, Alexander Hill, and Paul Kwiat
Acknowledged Federal Support: **Y**

DISSERTATIONS:

RPPR Final Report
as of 19-Sep-2023

Publication Type: Thesis or Dissertation

Institution: University of Rochester

Date Received: 30-Aug-2016

Completion Date: 8/2/16 3:52AM

Title: Stochastic path integral formalism for continuous quantum measurement

Authors: Areeya Chantasri

Acknowledged Federal Support: **Y**

Publication Type: Thesis or Dissertation

Institution: University of Rochester

Date Received: 19-Oct-2017

Completion Date: 5/13/17 3:41AM

Title: Precision Optical Measurements Using Weak Values and Nonclassical States

Authors: Kevin Lyons

Acknowledged Federal Support: **Y**

Publication Type: Thesis or Dissertation

Institution: University of Illinois Urbana-Champaign

Date Received: 06-Sep-2023

Completion Date: 5/5/19 5:00AM

Title: INVESTIGATIONS OF QUANTUM SENSING TECHNIQUES FOR DEFLECTION AND DISPLACEMENT METROLOGY

Authors: Courtney, Krafczyk

Acknowledged Federal Support: **Y**

Partners

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I certify that the information in the report is complete and accurate:

Signature: Paul Kwiat

Signature Date: 9/6/23 10:29AM

Advanced Quantum Sensing: W911NF-13-1-0402 / 63986PH

Paul Kwiat, University of Illinois

Andrew Jordan, University of Rochester

Final Report

Abstract: In this proposal, we investigated several different strategies for improving the sensitivity of quantum optical detection schemes. We did this by leveraging various measurement techniques in optical metrology: weak-value amplification, quantum erasure, the quantum Zeno effect, and correlations in quantum light, such as squeezed or entangled light. Recent advances in the use of weak-value amplification to detect small changes in a parameter, such as optical beam deflection, have shown that the technique of post-selection can greatly reduce technical noise in an experiment, leading to significant improvements in the limits of detection. One generic weakness of such techniques is the fact that most of the light is not actually detected. We investigated how to overcome this limitation here by recycling the undetected light using a pulsed scheme, so that eventually every photon is measured. We showed how this idea can lead to an improvement in the signal-to-noise ratio, effectively given by the power increase on the detector, all other things being equal. Since single-pass weak-value amplification already achieves the sensitivity of standard measurement techniques (such as homodyne detection) but with lower technical noise, the improvements from recycling exceed the sensitivity of the standard techniques, even when they are shot-noise limited. Our experimental implementation achieved a significant improvement in the signal-to-noise ratio, in agreement with theoretical calculations.

The precision of a beam-deflection measurement is limited both by sources of technical noise present in any laboratory setting, as well as fundamental sources of uncertainty derived from quantum mechanical considerations. Using light with quantum mechanical correlations allows us to simultaneously decrease the quantum uncertainty of the transverse position observable and reduce technical noise encountered in the lab. We used momentum-entangled light, in which the photons falling on either side of a position-sensitive detector will be correlated with one another. In the extreme case, photons will always fall in correlated pairs on the detector, leading to ideally no noise in the difference signal. Such a detector permits us to achieve the Heisenberg limit, the case when the minimum resolvable signal scales as the inverse photon number, rather than the inverse square-root photon number, the standard quantum limit. We have experimentally demonstrated a quantum advantage using such entangled light.

Finally, we considered whether an atomic force microscopic (AFM) could achieve improved spatial resolution, by using quantum erasure techniques. Although the answer is affirmative, the modest benefits would likely not justify the added experimental complication.

A supplement to this award was given to help investigations of multiplexing-enhanced quantum light sources. We used these to achieve a world-record efficiency single-photon light source, as well as a quantum memory-enhanced quantum communication protocol, yielding up 30x increase in the protocol success rate.

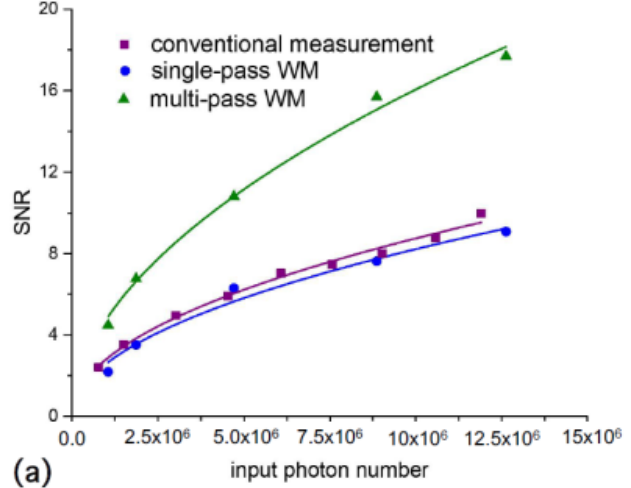


Figure 2: Experimental data. The green curve demonstrates the advantage in SNR using recycled weak-value measurements.

In addition, we carried out a theoretical analysis of improved optical beam displacement measurement using biphotons [3] (described in more detail below), and also theoretically published another recycling weak-measurement scheme using an optical cavity rather than polarization control [4]. Our work began with a simpler two-pass scheme to demonstrate a proof-of-principle improvement [5]. We also carried out theoretical investigations of advantages of weak-value amplification schemes in the presence of time-correlated noise with the Steinberg group [6], and also showed good noise suppression performance of phase measurements in the inverse weak-value regime [7]. More general investigation of quantum metrology showed that Heisenberg scaling could be reached with von Neumann interactions via momentum measurements [8]. In reference [9], we showed that for systematic noise, weak-value amplification suppresses the systematic contribution by a factor of the weak value – a dramatic and unexpected result. Interestingly, the best cited paper supported by this grant was Ref. [10], the development of the time-dependent theory of quantum metrology. The general results were applied to the Landau-Zener transition in [11], and other theoretical investigations of quantum measurement and the arrow of time were investigated in [12, 13].

Main Objective 2: Entanglement-enhanced Metrology

We now give a more detailed description of our final experimental measurements, showing entanglement-enhanced metrology of beam shifts. Optical split detection is a common technique for measuring displacement. In a typical measurement scenario, a bright laser beam reflects from the object being probed and then impinges on a detector with “left” (L) and “right” (R) cells: the difference between the L and R signals provides an estimate of the beam’s horizontal position and thus can also give an estimate of the horizontal displacement d (or angular deflection) of the object. The best possible precision of this measurement, quantified by the minimum possible variance of the measurement outcome, is related to the Gaussian beam transverse width σ at the detector: $\text{Var}(d) = \pi\sigma^2/8$. This result is applicable in the small displacement regime, $d \ll \sigma$.

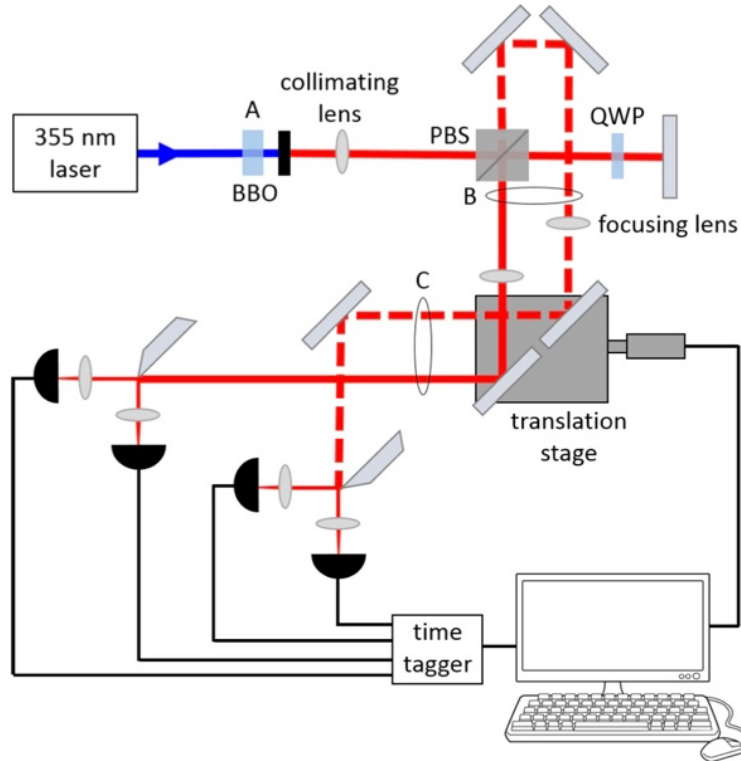


Figure 3: Diagram of the experimental setup. We use collinear, Type-II SPDC to generate correlated photon pairs with one photon horizontally polarized (indicated with a solid red line) and the other vertically polarized (dashed red line). SPDC pairs naturally have correlated positions, but for this experiment, we require anti-correlation: we separate the photons and impart one extra reflection to one of them. The photons then each probe mirrors mounted on the same moving translation stage. Finally, split detection is implemented using the edges of “D-shaped” mirrors and having one half of the beam reflect from the mirror to one single-photon detector, and the other half pass by the edge to a different detector.

For this work, we experimentally implemented a proposal to perform split detection measurements using biphotons (co-propagating pairs of photons) and coincidence detection [3]. For this 2-photon scheme, there are 4 possible coincidence detection outcomes (LL , LR , RL , RR), and the beam position estimator is formed by calculating the average result for the two photons, i.e., RR and LL correspond to ± 1 , while LR and RL both correspond to 0 (Fig. 3). When the photons of each pair are uncorrelated, this approach is identical to the standard measurement, but we showed in Ref. [3] that it can offer an advantage when the photons’ positions are anti-correlated: the measurement precision then depends not only on the transverse beam width, but also on the correlation distance between the photons ϵ , i.e., the spread in the mean position of the two photons. In the regime $d \ll \epsilon$, the best achievable precision is $\text{Var}(d) = \sigma\epsilon/4$. This is interesting for metrology applications because it means that for an optical power distribution characterized by transverse length σ , we can achieve a smaller variance (better precision). To

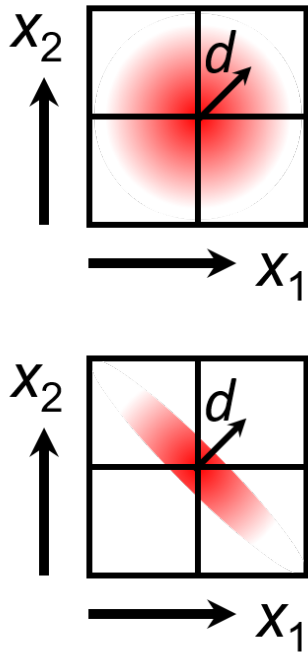


Figure 4: Schematic of coincidence split detection of JPIs for uncorrelated (top) and anti-correlated biphotons (bottom). The x_1 and x_2 axes represent the horizontal position of photons 1 and 2, respectively. In split detection, each axis is divided in half, so that the distribution is approximately centered on 4 quadrants. A horizontal displacement d of the two photons leads to a shift along the 45° axis. While both of these biphoton distributions have similar optical power distributions for each biphoton, the lower one is narrow along the 45° axis, enabling better precision.

understand why this improvement occurs, we can look at the 2-photon spatial probability distribution or the joint position intensity (JPI) distribution (Fig. 4). While the width of the optical power distribution for each photon is related to the JPI's marginal spread along the horizontal and vertical axes, the sensitivity to small displacements depends on the marginal spread along the 45° axes, which can be significantly smaller.

The photon pairs we produce using spontaneous parametric down conversion (SPDC) are naturally entangled in position (Fig. 4, bottom), so here we take advantage of this resource to demonstrate enhanced-precision split detection measurements of beam displacement. The theory developed in Ref. [3] does not address certain experimental non-idealities we encountered in our setup (non-Gaussian beams; “dead zones” between the L and R detection outcomes), so our results are not directly comparable with the equations derived there. Instead, we compare our data with Monte Carlo simulations based on the measured 2-photon probability distribution, showing good agreement (Fig. 5).

The precision achieved by taking advantage of spatial correlations is an improvement over an uncorrelated beam with optical power distribution of width σ , but it can readily be seen that an uncorrelated beam with the smaller width ϵ , would perform even better. This is because most of the optical power in the two-photon measurement is “wasted” on measurement instances that give a zero result, while the small uncorrelated beam has all of its power concentrated in the important region near the cell boundaries. Another idea proposed in Ref. [3] is to take advantage of a larger fraction of the correlated JPI by using detectors with more than just the 2 cells L and R ; there it was shown that the precision generally improves with increasing pixel number. Since

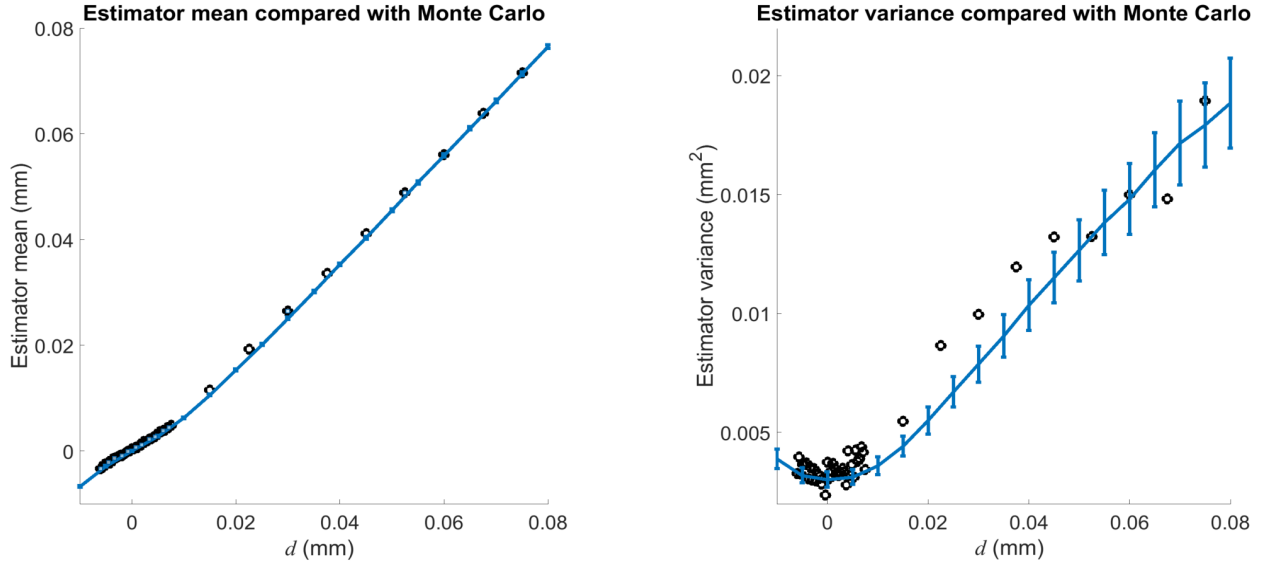


Figure 5: Results of split-detection measurements (black circles) compared with Monte Carlo simulations of the experiment (blue curve) for multiple values of d , including the regime $d \ll \epsilon$ as well as $d \sim \epsilon$, where the precision begins to degrade, but is still an improvement over uncorrelated pairs. On the left we plot the estimator mean, i.e., the result that would be obtained for an actual measurement; on the right we plot the variance of the measurement results. As expected, the best performance occurs for small displacements. Given transverse width σ of our JPI, an uncorrelated pair would give variance of 0.098 mm^2 , far outside the range of this plot, demonstrating the precision advantage we aimed to observe. We determined that the kink near $d=0$ in the estimator mean curve is due to reduced reflectivity at the edge of the D-shaped mirror used for split detection; this was one of the non-idealities that required us to use Monte Carlo simulation instead of directly using the equations from Ref. [3].

we did not have access to multi-cell single-photon detectors for this experiment, we instead simulated detectors with various numbers of pixels N by making full measurements of the JPI for several different displacement values, then segmenting the measured JPIs into N^2 cells (N lateral positions for each detector) and performing Monte Carlo simulations of a split-detection measurement. The results agree well with our calculations for ideal Gaussian beams (Fig. 6).

As illustrated in Fig. 6, although the general trend is that precision improves for larger N , there can be exceptions. For example, going from $N=2$ to $N=3$ actually leads to a significant *reduction* in performance: the single-cell boundary of the 2-cell detector is better positioned on the Gaussian JPI than the 2-cell boundaries of the 3-cell detector, which are placed in JPI regions with relatively low intensity. This motivated us to consider ways to modify the JPI itself in order to improve the performance of the 3-cell detector. By using a HG_{10} pump mode, i.e., with a null in the center of the transverse beam profile (created by applying a relative π phase shift between the two halves of the pump), we generate a JPI with a null at the center and maximum intensity relatively far from the center (Fig. 7). We demonstrate that such a distribution is better suited to the 3-cell scenario than the Gaussian JPI (Fig. 6).

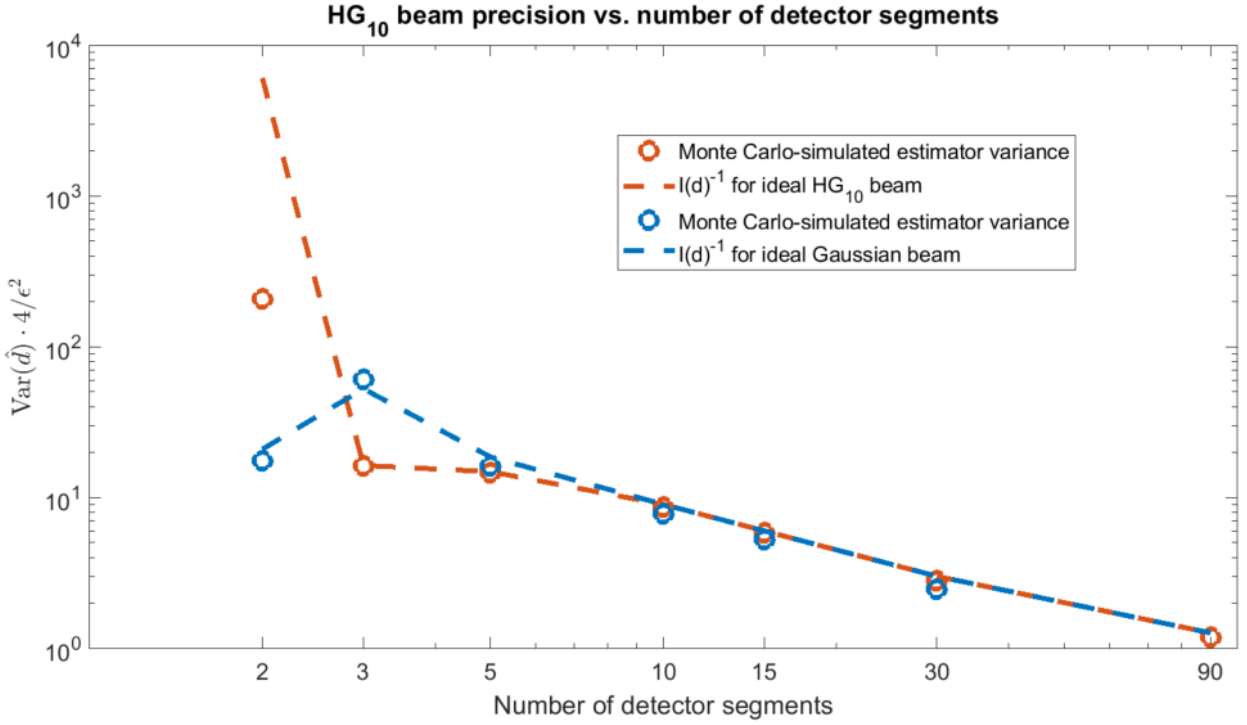


Figure 6: Results of simulations of multi-cell coincidence detection of correlated biphotons for Gaussian (blue) and HG_{10} (red) JPIs; the circles show our simulations based on actual measured JPIs for different displacements, and the dashed lines show calculations for ideal beams. Each data series shows the variance obtained for small displacements. While the general trend is for precision to improve with more detector cells, $N=3$ is an exception: for a Gaussian JPI, $N=2$ would actually be better. However, we see here that a HG_{10} JPI would be well-suited to the 3-cell detector.

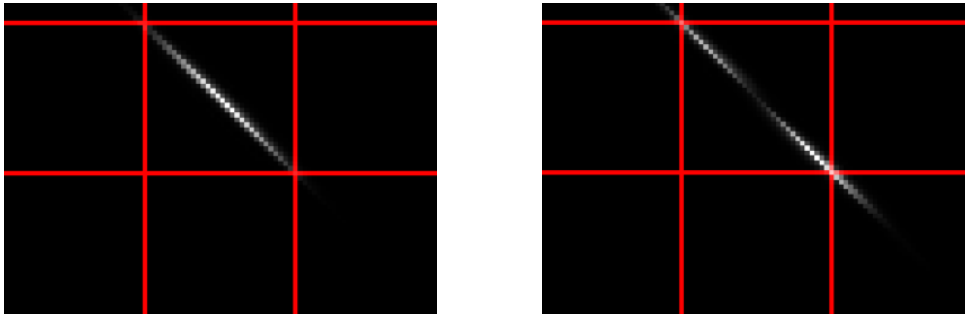


Figure 7: Measured JPIs produced by Gaussian (left) and HG_{10} (right) pump modes, with red lines indicating the cell regions for 3-cell detection. For the Gaussian JPI, the cell boundaries intersect regions of low intensity, leading to poor performance for displacement measurements. In contrast, the cell boundaries are well-positioned for the HG_{10} mode.

Main Objective 3: Atomic Force Microscope and Quantum Eraser

As part of this project we also examined the possibility of improving sensitivity in atomic force (and magnetic-resonance force) microscopy (AFM), using quantum eraser methods. The essential idea was to use a particular post-selection to improve the visibility of the signal used to determine the angle of the AFM tip. As shown in Fig. 8, a typical AFM works by placing the end of a fiber close to an oscillating cantilever. By interfering light reflected from the end of the fiber and from the cantilever, the displacement of the cantilever can be determined. In the usual design, the visibility of the fringes is determined by the reflectivity of the fiber end and of the cantilever. (Note that the optical power incident on the cantilever is constrained in order to limit the heating caused by residual absorption of the light hitting it.) We compared this case to one using a quantum eraser, in which, e.g., a wire-grid polarizer would be coated on the fiber end to transmit V (since V is preferentially reflected by the cantilever) and reflect H. Another polarizer would be used at the output to control the analysis angle and recover interference. Details of the calculation are given below; in brief, we have found that adding a quantum eraser *would* improve the SNR, but only marginally compared to typical AFM performance. The reason is that while one can always recover perfect visibility fringes using a quantum eraser, the *magnitude* of the signal decreases, which eventually limits the measurement sensitivity.

The interference fringes in the output power in all cases will be of the form

$$P_{out} = A + B\cos\varphi,$$

where φ is the phase induced by the displacement of the cantilever. For a small shift in φ , the change in the power will be approximately $B\Delta\varphi$, which is our signal. We examine a system limited by the quantum shot-noise of the detected light; hence, the noise will be proportional to the square root of the detected power, which is approximately \sqrt{A} (since we will operate around $\varphi = \frac{\pi}{2}$, where the signal changes most sensitively). The signal-to-noise ratio (SNR) is then

$$SNR \sim \frac{B\Delta\varphi}{\sqrt{A}}.$$

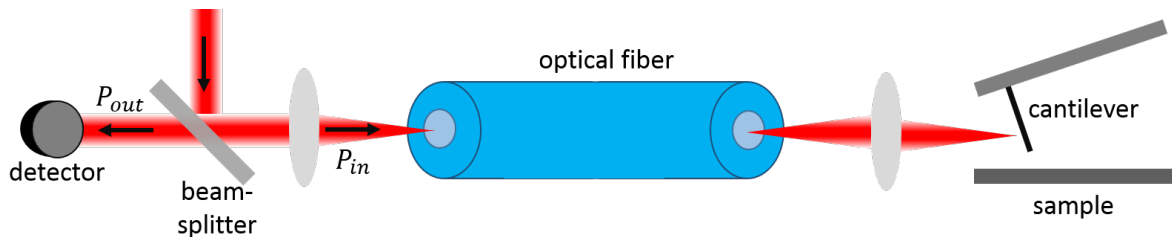


Figure 8: An AFM setup as it is typically used. Light is coupled into a fiber and partially reflects from the fiber end and cantilever. The two paths interfere and the fringes in power are measured at the detector to determine the displacement of the cantilever.

1. Without a Polarization Quantum Eraser

A typical AFM is designed such that light coupled into a fiber is partially reflected from the fiber tip. A fraction of the light that is transmitted through the end reflects from the cantilever and is recoupled into the fiber. By examining the fringes in power due to the interference of these two reflections, one can deduce the shift in the cantilever position. The measured power and SNR will be

$$P_{out} = \left| \sqrt{P_{in}} (\sqrt{R_F} + \sqrt{(1 - R_F)R_C} e^{i\varphi}) \right|^2$$

$$= P_{in} [R_F + (1 - R_F)R_C + 2\cos\varphi \sqrt{(1 - R_F)R_F R_C}]$$

$$SNR_{wo} = \frac{2\sqrt{(1 - R_F)R_F R_C}}{\sqrt{R_F + (1 - R_F)R_C}} \Delta\varphi,$$

where P_{in} is the incident power, R_F is the reflectivity of the fiber end, and R_C is the reflectivity of the cantilever, here including the efficiency of coupling back into the fiber. In a typical AFM, $R_F \sim 0.05$ and $R_C \sim 0.01$. From this, we find

$$P_{out} \cong P_{in}(0.06 + 0.045\cos\varphi)$$

$$SNR_{wo} \cong 0.045 \sqrt{\frac{P_{in}}{0.06}} \Delta\varphi.$$

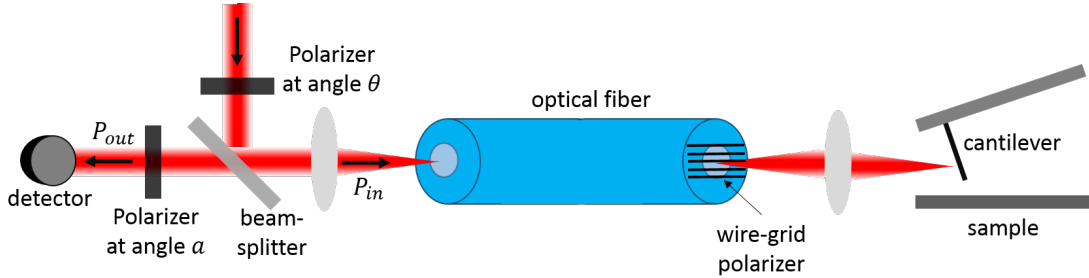


Figure 9: An AFM setup including a polarization quantum eraser. Input light is polarized at angle θ and coupled into a fiber. A wire-grid polarizer gives complete which-way information by reflecting H polarization from the fiber end and transmitting V polarization to the cantilever. At the output, a polarizer at angle a erases the which-way information, recovering interference.

2. With Polarization Quantum Eraser

If the reflection of the fiber and cantilever are different, then there is some information in the system about which path a photon took (for example, if the reflection from the fiber is higher than that of the cantilever, we can say that a detected photon probably bounced off the fiber). This which-path information will degrade the interference of the two beams and therefore reduce our signal. It is possible to recover the interference by first adding a polarization signature to the path, then using a polarizer to erase that information, potentially increasing the SNR. An implementation of the quantum eraser is shown in Fig. 9.

We send in the state $\sqrt{P_{in}}(\cos\theta|H\rangle + \sin\theta|V\rangle)$. Assuming a perfectly reflective polarizer ($R_{F,V} = 0, R_{F,H} = 1$), this evolves to $\sqrt{P_{in}}(\cos\theta|H\rangle + e^{i\varphi}\sqrt{R_C}\sin\theta|V\rangle)$, after light reflected from the cantilever is recoupled into the fiber. At the output, the light passes through a polarizer at angle a , leaving the photons in the state $|a\rangle\sqrt{P_{in}}(\cos\theta\cos a + e^{i\varphi}\sqrt{R_C}\sin\theta\sin a)$. We have that the output power is

$$P_{out} = P_{in}(\cos^2\theta\cos^2a + R_C\sin^2\theta\sin^2a + 2\cos\varphi\sqrt{R_C}\cos\theta\cos a\sin\theta\sin a)$$

$$SNR_w = 2\sqrt{R_C}\cos\theta\cos a\sin\theta\sin a\sqrt{\frac{P_{in}}{\cos^2\theta\cos^2a + R_C\sin^2\theta\sin^2a}}\Delta\varphi.$$

Again using $R_C \sim 0.01$, we have

$$P_{out} \cong P_{in}(\cos^2\theta\cos^2a + 0.01\sin^2\theta\sin^2a + 2\cos\varphi\sqrt{0.01}\cos\theta\cos a\sin\theta\sin a)$$

$$SNR_w \cong 0.20\cos\theta\cos a\sin\theta\sin a\sqrt{\frac{P_{in}}{\cos^2\theta\cos^2a + 0.01\sin^2\theta\sin^2a}}\Delta\varphi.$$

Comparison of the Two Cases

As mentioned above, the power we can have incident on the cantilever (P_c) is limited by heating effects. Thus, our P_{in} in each case will be determined by P_c . For the case without the quantum eraser $P_{in} = \frac{P_c}{0.01}$, with the quantum eraser, $P_{in} = \frac{P_c}{0.01\sin^2\theta}$. For comparison, we set $P_c = 1$.

Plugging our values for P_{in} into the above expressions, we obtain

$$SNR_{wo} \cong 1.84\Delta\varphi.$$

For the case with the quantum eraser, we optimize θ and a , to find the largest value

$$SNR_w \cong 2\Delta\varphi,$$

for $\theta = 0$ and $a = \frac{\pi}{2}$ (i.e., send in as many H photons as possible to increase the output power, but keep most of the V photons from the cantilever). Note that the specific SNR values we have found here are not independently meaningful, since we left the SNR in terms of power instead of photon number. However, the ratio of the two is a valid measure of comparison.

In conclusion, although the quantum eraser technique *does* afford some improvement, given the typical cantilever reflectivity, the advantage is probably not sufficient to justify the added experimental complexity. It may, however, be interesting to include weak measurements and/or quantum light as a method to improve AFM performance.

Supplemental Objective: Multiplexing-enhanced Sources and Protocols

For multiple single-photon generation, a typical quantum optics experiment uses multiple Heralded Single Photon Sources (HSPSs), and experimentalists wait for events that multiple sources generate a heralded single photon simultaneously. However, due to the HSPSs' probabilistic generation, the success probability of multi-photon simultaneous generation decreases exponentially with the number of photons. In order to overcome the probabilistic nature of HSPSs, we employed quantum memories (which are adjustable delay lines in our project) to multiplex photons from different HSPSs. The general idea is depicted in Fig. 10. In each HSPS, photons generated in a trigger mode are sent to a single-photon detector, whose click "heralds" in which time slot the corresponding twin photon is present. M HSPSs pumped with a period τ , generate photon pairs probabilistically, though in general not simultaneously. Each quantum memory (triggered by a heralding signal from its corresponding HSPS) stores heralded photons for an arbitrary integer time of τ , until all other sources produce their pairs. After the last source heralds a "last-born" photon, the $M - 1$ memories storing the earlier-born photons release them simultaneously, thereby producing M simultaneous photons. Given each source's heralding probability per pump pulse $p \sim \mu\eta \ll 1$ (where η is the system detection efficiency of the trigger mode), a maximum number of storage time slots N , and lossless quantum memories, the M -fold coincidence probability is given by $\{1 - (1-p)^N\}^M \sim (pN)^M$. Hence, one can obtain up to $\times N^{M-1}$ enhancement over a non-multiplexed case that requires M independent sources to simultaneously herald M photons (with probability $p^M N$).

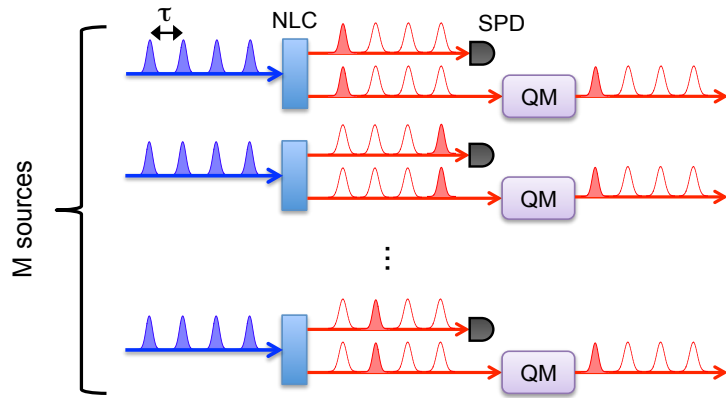


Figure 10. A scheme to generate M single photons from M HSPSs synchronized by quantum memories. NLC, nonlinear crystal; SPD, single-photon detector; QM, quantum memory.

Note that this time-multiplexed multi-photon generation scheme even has a higher generation rate compared to the *periodic* time-multiplexed HSPSs [15] that we originally proposed for multi-photon generation: M periodic time-multiplexed sources need to wait for periodic output time windows even if all memories have loaded photons earlier. In contrast, our proposed scheme needs to store $M - 1$ photons only for the *difference* of the generation time slots, substantially reducing total storage loss in imperfect (and practical) quantum memories. Also, the synchronization process can be repeated immediately after the last source heralds its photon, leading to somewhat higher rates.

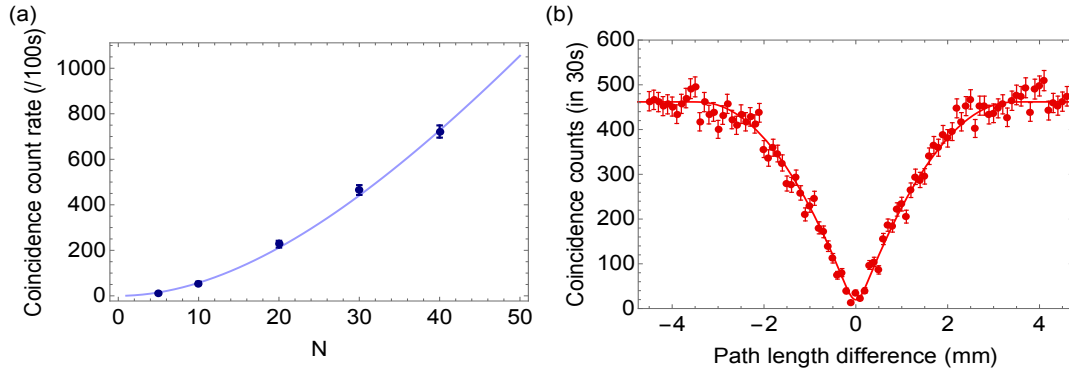


Figure 11. (a) Coincidence count rate of photons from synchronized HSPSs vs. maximum storage cycle number N . (b) Observed Hong-Ou-Mandel interference of multiplexed photons with $N = 40$.

We performed a proof-of-concept experiment of this multiplexed HSPSs, using our new low-loss HSPSs and a storage-ring-based memory [14]. Fig. 11 (a) shows two-photon coincidence count rate versus N with multiplexing two HSPSs. As expected for $M = 2$ in our experiment, the coincidence count rate increases as $\sim N^2$. The coincidence count rate for $N = 40$ corresponds to $> 30x$ enhancement over the non-multiplexed case. We characterized the indistinguishability of time-multiplexed photons by Hong-Ou-Mandel interference (HOMI), of which visibility is a direct measure (see Fig. 11 (b)). Our observed high visibility (95.7%) indicates that our storage-ring-based memory well preserves the time-bandwidth characteristics ($\Delta t = 6.1$ ps, $\Delta \lambda = 0.8$ nm) and indistinguishability of the heralded photons, due to very low group-velocity dispersion and cycle-length fluctuation.

Applying this synchronization technique, we also proposed and demonstrated time-multiplexed measurement-device-independent quantum key distribution (MDI-QKD). A standard MDI-QKD scheme and our advanced version are depicted in Fig. 12. In standard MDI-QKD, Alice and Bob, who want to share secure cryptographic keys with each other, both need to simultaneously send qubit-encoded photons to Charlie, who identifies the correlation between Alice's and Bob's qubits (but not those qubits themselves) via Bell-state measurement (BSM), i.e., projection measurement of them into the Bell-state basis. Therefore, since MDI-QKD requires two-photon coincidences in the BSM, efficient simultaneous generation of single-photon states is more critical to realize high secure key rates, while a traditional BB84 protocol in principle needs only one single-photon source (but then requires additional assumptions about the detectors). In our scheme, in addition to the standard BSM configuration, Charlie possesses a quantum memory module so that an early-arrival photon from Alice's (Bob's) HSPS is delayed to be sent to the BSM setup simultaneously with a late-arrival photon from Bob's (Alice's) source. Thus, the success event rate of the BSM and thereby the secure key rate are significantly increased compared to the standard (non-multiplexed) case.

With the help of enhanced coincidence count rates by time multiplexing, for the first time we obtained secure keys via HSPS-based MDI-QKD [16]; however, no positive key could be guaranteed for the non-multiplexed case because of the large uncertainty in the estimates of the QKD bit error rates, due to $\sim 30\times$ fewer photon count rates compared to the synchronized case. Therefore, the enhanced coincidence count rate with our time-multiplexing technique was critical to enable useful HSPS-based MDI-QKD.

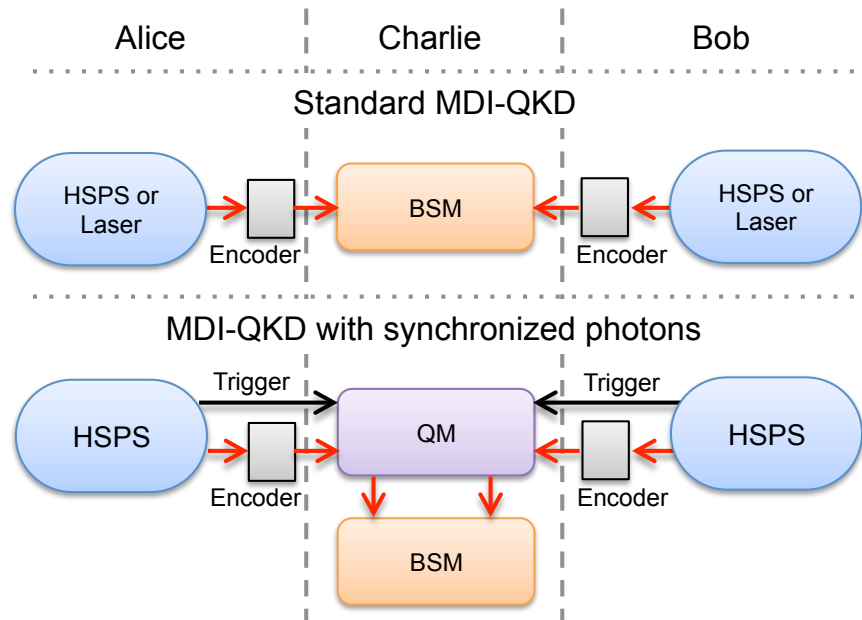


Figure 12. Comparison of a standard MDI-QKD and our proposed scheme with synchronized photons. BSM, Bell-state measurement; QM, quantum memory.

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