Coherence and Quantum Optics and Quantum Information and Measurement 2013

17 - 20 June 2013 University of Rochester, Rochester, New York, USA

The Rochester Conferences on Coherence and Quantum Optics (CQO) have been held every six years since their inception in 1960, essentially coincident with the first observation of lasing. The Quantum Information and Measurement (QIM) meeting was initiated last year by the Optical Society to cover many of the exciting developments in quantum information and quantum measurement. The conferences will be held during the week of June 17-20, 2013 and will be held on the campus of the University of Rochester with housing available both off-campus and in the University of Rochester dormitories. These conferences bring together the leaders in theoretical and experimental coherence, quantum optics, quantum information and quantum measurement from throughout the world to review the progress of the field and to coalesce ideas about future directions. Through a series of tutorials, historical reviews, invited papers, and poster sessions, a perspective is provided on the research in the field for the past few years as well as highlighting the latest developments.

The CQO conferences are truly international and have brought together leading researchers from around the world. For example, Nobel laureate Edward Purcell, along with other pioneers in the field including R. Hanbury Brown, and S. Pancharatnam, attended the first conference in June 1960. In the following conferences attendees have included Nobel laureates Willis Lamb, Arthur Schawlow, Nicholas Bloembergen, Roy Glauber, Claude• Cohen-Tannoudji, William Phillips, Wolfgang Ketterle and Serge Haroche.

General topics of interest include all aspects of experimental and theoretical coherence, quantum optics, quantum information and quantum measurement. A special historical symposium will be presented on the Jaynes-Cummings model and a joint-meeting symposium will be held on weak values.

The CQO-10 topics will include: cavity quantum electrodynamics, artificial atoms, optomechanics, non-classical states, topological quantum states, foundations of quantum coherence, Casimir effect, quantum simulation, entanglement, weak measurement, ultra-cold gases, singular optics, orbital angular momentum.

The QIM meeting will cover topics of quantum metrology, entanglement, quantum memories, quantum key distribution, quantum computing, and quantum control.

Conference Organization and Information Dissemination

CQO X Local Organizing Committee:
A. Badolato, N. P. Bigelow, J. H. Eberly, J. C. Howell, A. N. Jordan, C. R. Stroud, A. N. Vamivakas, X-C Zhang

QIM 2 Local Organizing Committee:
J.C. Howell and A.N. Jordan

CQO X External Advising Committee:

- Girish Agarwal, Oklahoma State University, USA.
- Alain Aspect, Ecole Polytechnique, France.
- Steven T. Cundiff, JILA, USA.
- Luiz Davidovich, Federal University of Rio de Janeiro, Brazil.
- Joseph H. Eberly, University of Rochester, USA.
- Guang-Can Guo, University of Science and Technology of China, China.
- Ataç İmamoğlu, ETH Zurich, Switzerland.
- Peter Knight, Imperial College, London, UK.
- Kazimierz Rzążewski, Polish Academy of Sciences, Poland.
- Ian Walmsley, Oxford University, UK.
- Ting Yu, Stevens Institute of Technology.

QIM 2 External Advising Committee:

- Jonathan Dowling, Louisiana State University, USA.
- Claude Fabre, University Pierre et Marie Curie Paris 6, France.
- James Franson, UMBC, USA.
- Jian-Wei Pan, University of Science and Technology of China, China.
- Howard Wiseman, Griffith University, Australia.

Invited Speakers

Abouraddy, Ayman (Central Florida)
Aspect, Alain (Paris – L.C.F.)
Atature, Mete (Cambridge)
Banzer, Peter (Max Planck – Erlangen)
Bieler, Mark (P.T.B. Braunschweig)
Blatt, Rainer (Innsbruck)
Boyd, Robert (Rochester & Ottawa)
Carmichael, Howard (Auckland)
Cummings, Fred (Marin Co., CA)
Davidovich, Luiz (Rio de Janeiro)
Desyatnikov, A.S. (ANU, Canberra)
Dowling, Jonathan (LSU)
Eisenberg, Hagai (Jerusalem)
Fabre, Claude (Paris – L.K.B.)
Fedorov, Mikhail (Russian Academy of Sciences)
Franson, James (U.M.B.C.)
Fuchs, Christopher (Perimeter)
Furusawa, Akira (Tokyo)
Gaeta, Alex (Cornell)
Gauthier, Dan (Duke)
Giacobino, Elisabeth (Paris – L.K.B.)
Girvin, Steven (Yale)
Haroche, Serge (Paris – E.N.S. and C.F.)
Hofmann, Holger (Hiroshima)
James, Daniel (Toronto)

Kim, Myungshik (Imperial, London)
Kimble, Jeff (Cal Tech)
Kira, Mackillo (Marburg)
Kurizki, Gershon (Weizmann)
Kuzmich, Alex (Georgia Tech)
Kwiat, Paul (Illinois – U.C.)
Lett, Paul (Maryland – NIST)
Lipson, Michal (Cornell)
Lukin, Mikhail (Harvard)
Marquart, Christoph (Max Planck - Erlangen)
Monken, Carlos (Brazil – UFMG)
Monroe, Chris (Maryland)
Narducci, Frank (Naval Air Systems Command)
Nori, Franco (Riken and Michigan)
Nussenzveig, Paulo (LMCAL – São Paulo)
Orozco, Luis (Maryland)
Padgett, Miles (Glasgow)
Pan, Jian-Wei (USTC – China)
Plenio, Martin (Ulm)
Rempe, Gerhard (Max Planck - Garching)
Rzazewski, Kazimierz (Polish Academy of Sciences)
Sanchez-Soto, Luis (M.P.I. Erlangen)
Schwab, Keith (CalTech)
Segev, Mordechai (Technion)
Senellart, Pascale (C.N.R.S. – Paris)
Sergienko, Alexander (Boston University)
Shih, Yanhua (UMBC)
Silberberg, Yaron (Weizmann)
Simon, Christoph (Calgary)
Solomon, Glenn (NIST)
Soskin, Marat (NAS – Ukraine)
Steinberg, Aephraim (Toronto)
Sweeney, Tim (NRL)
Thew, Robert (GAP – Geneva)
Tittel, Wolfgang (Calgary)
Tollaksen, Jeff (Chapman)
Vaidman, Lev (Tel Aviv)
Vedral, Vlatko (Oxford & Singapore)
Visser, Taco (Delft & Vrije, Amsterdam)
Vogel, Werner (Rostock)
Walborn, Stephen (U.F.M.G. Brazil)
Walmsley, Ian (Oxford)
White, Andrew (Queensland)
Wiseman, Howard (Griffith)
Yu, Ting (Stevens)
Zeilinger, Anton (Vienna)
Zubairy, Suhail (Texas A&M)

Endorsements and Sponsorships

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The Tenth Rochester Conferences on Coherence and Quantum Optics (CQO-X) and The Second Quantum Information and Measurement (QIM) Meeting Program Book

June 17-20 2013

The University of Rochester

Rochester, NY, USA

Table of Contents

Tenth Rochester Conference on Coherence and Quantum Optics

Welcome to the Tenth Rochester Conference on Coherence and Quantum Optics. This meeting is the latest in a series held at approximately six-year intervals since the first one, which was held just a few weeks before the announcement of the first successful operation of the optical maser in 1960. These have been landmark meetings chronicling the progress of the field from its beginning.

Many historic advances in quantum optics have been debated at these meetings, and we will celebrate the fiftieth anniversary of the paper by E. T. Jaynes and F. W. Cummings that provided the model underlying many of these advances. In addition, the conferences have featured tutorial lectures, extended reviews, and also historical reviews by pioneers in coherence and quantum optics. We will continue these traditions with a number of outstanding tutorials and reviews. These include extended lectures by Serge Haroche, Franco Nori , James Franson, Alex Gaeta, Anton Zeilinger, Alain Aspect, Miles Padgett, Ian Walmsley and Aephraim Steinberg. Again, as at CQO8 and CQO9, we are holding this meeting in conjunction with a sister meeting, the Second International Meeting on Quantum Information and Measurement. Quantum information is rapidly expanding, making extensive use of quantum optics, so that the two meetings with overlapping sessions on Tuesday and Wednesday offer a nice synergy.

We have been assisted in putting together this program by an international advisory committee including: G. S. Agarwal, A. Aspect, S. T. Cundiff, L. Davidovich, G. C. Guo, A. Imamoğlu, P. L. Knight, K. Rzążewski, W. P. Schleich, I. A. Walmsley and T. Yu. Also assisting with local arrangements as well as review of submissions were Antonio Badolato, John Howell, Andrew Jordan, Nickolas Vamivakas and Xi-Cheng Zhang. Financial support has been provided by the U. S. Army Research Office, the Optical Society of America, Taylor and Francis Publishers, Newport Corporation and Thorlabs, as well as the Institute of Optics and the Department of Physics and Astronomy of the University of Rochester.

Following another tradition of this series of meetings we will have a relaxing banquet on Tuesday with good food and interesting wines together with OSA and ICO award presentations, as well as a talk by Paul Kelley, *A century of Advances in Optics.* We will also publish a volume highlighting the progress that has been made in the past six years in the fields of coherence and quantum optics as well as the beginnings of the advances that will lead us through the next six years and further. Indeed we hope that you find this week at the University of Rochester both intellectually stimulating and enjoyable.

Conference Secretaries

Nicholas Bigelow

Joseph Eberly

Carlos Stroud

University of Rochester, USA

Welcome to the Quantum Information and Measurement meeting! We are pleased to have you here in Rochester, New York, for what promises to be an exciting and informative meeting on this fascinating topic.

Quantum information and quantum measurement are exciting areas of current research. The field is rapidly growing in terms of interest and scientific development. Optical methods play a key role in many implementations of quantum information. Because of the strong overlap with the field of quantum optics, we have decided to collocate this meeting with the Tenth Rochester Conference on Coherence and Quantum Optics (CQO10).

Topics for the meeting include the following: quantum control, quantum imaging, quantum cryptography, entanglement scaling, higher-order entanglement, trapped ions information processing, dipole blockade, orbital angular momentum, optical storage of quantum information, weak values and single-photon nonlinear optics.

The conference banquet will be held on Tuesday evening. Poster sessions for the combined meetings will be held on Monday and Wednesday evenings.

Financial support has been provided by the U. S. Army Research Office, the Optical Society of America, Taylor and Francis Publishers, Newport Corporation and Thorlabs, as well as the Institute of Optics and the Department of Physics and Astronomy of the University of Rochester. We want to thank and acknowledge the superb job of the program committee in identifying themes and invited speakers for this meeting. We also extend our deep appreciation to the staffs of the Meetings Department of OSA and of the Conference and Events Office of the University of Rochester for the superb job they have done in handling the arrangements for this meeting.

Conference Co-Chairs

John Howell, *University of Rochester, USA*

Andrew Jordan, *University of Rochester, USA*

Committee

Tenth Rochester Conference on Coherence and Quantum Optics (CQO-X)

External Organizing Committee
Girish Agarwal, *Oklahoma State Univ., USA*
Alain Aspect, *Ecole Polytechnique, France*
Steven T. Cundiff, *JILA, USA*
Luiz Davidovich, *Federal Univ. of Rio de Janeiro, Brazil*
Guang-Can Guo, *Univ. of Science and Tech. of China, China*
Ataç İmamoğlu, *ETH Zurich, Switzerland*
Peter Knight, *Imperial College, London, UK*
Kazimierz Rzążewski, *Polish Academy of Sciences, Poland*
Ian Walmsley, *Oxford Univ., UK*
Ting Yu, *Stevens Inst. of Tech., USA*

Local Organizing Committee
A. Badolato, N. P. Bigelow, J. H. Eberly, J. C. Howell, A. N. Jordan, C. R. Stroud, A. N. Vamivakas, X-C Zhang

Second International Conference on Quantum Information and Measurement (QIM-2)

External Organizing Committee
Jonathan Dowling, *Louisiana State Univ., USA*
Claude Fabre, *Univ. Pierre et Marie Curie Paris 6, France*
James Franson, *Univ. of Maryland, Baltimore County, USA*
Jian-Wei Pan, *Univ. of Science and Tech. of China, China*
Howard Wiseman, *Griffith Univ., Australia*

Local Organizing Committee
J. C. Howell and A. N. Jordan

General Information

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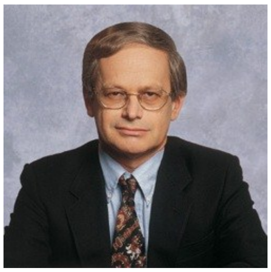
Special Events

Banquet

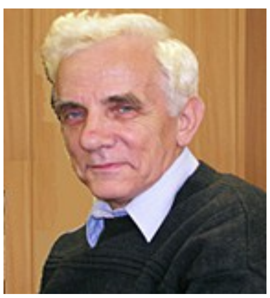
Please join us on Tuesday evening, 7:00 pm, in the Meliora Ballroom for a relaxing banquet that will offer good food and an interesting selection of wines. The below Awards Ceremony and Address by Paul Kelly will follow.

Awards



The OSA Max Born Award:

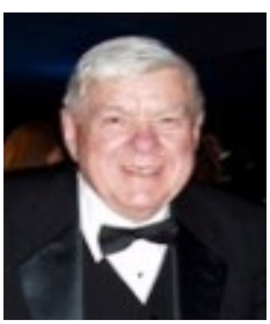
Yaron Silberberg, Weizmann Institute, is the recipient of the 2012 Max Born Award of the Optical Society of America, for seminal contributions in nonlinear and quantum optics, among them the first observation of optical discrete solitons, the prediction of spatio-temporal solitons and light bullets, pioneering experiments with temporal shaping of entangled photons and quantum control, and groundbreaking work in nonlinear microscopy.



The ICO Galileo Galilei Medal:

Mikhail V. Fedorov, Prokhorov Institute of the Russian Academy of Sciences, is the recipient of the 2012 Galileo Galilei Medal of the International Commission on Optics, awarded foroutstanding contributions to the field of optics which are achieved under comparatively unfavorable circumstances.

Address



Optics in the Twentieth Century, Paul L. Kelley; *The Optical Society (OSA), USA*. Optics has undergone striking transformations in the last century. Industry, government, and academia have played important roles in this change. Transformative events, such as war, and inventions, such as the laser, have been more than significant.

Explanation of Session Codes

M2A.3

Day of the Week	Series	Session Venue	Presentation Number
M—Monday	1—1st series	A—1st oral session	Presentation order within session.
T—Tuesday	2—2nd series	B—2nd oral session	
W—Wednesday			
Th—Thursday			
F—Friday			

The first letter of the code designates the day. The second element indicates the session series in that day (for instance, 1 would denote the first session or group of parallel sessions in that day). The third element indicates the session venue in a series alphabetically (A=1st parallel session, B=2nd). The lettering restarts with each new series. *Note: The absence of a letter indicates there is only one session in that time slot*. The number on the end of the code (separated from the session code with a period) signals the position of the talk within the session (first, second, third, etc.). For example, a presentation coded M2A.3 indicates that this paper is on Monday (M) in the second series of sessions (2), and is the first parallel session (A) in that series and the third paper (3) presented in that session.

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Hoyt Auditorium
08:15 am -- 10:00 am
M1 • Session M1
Presider: Emil Wolf, Univ. of Rochester, USA

Monday, June 17

M1.1 • 08:15 am
Introductory Remarks, Emil Wolf; *Univ. of Rochester, USA*

M1.2 • 08:30 am Invited
Diagonalize a 2x2 and Wait 50 Years, Frederick W. Cummings; *Univ. of California, Riverside, USA.* A thesis student at Stanford in the late 1950s reminisces about working under the guidance of Professor Edwin T. Jaynes. Some of the theoretical puzzles at that time are remembered. These involved topics such as comparison of the semi-classical theory with the problem-plagued perturbation ‘QED'.

M1.3 • 08:45 am Invited
My Life in Physics: from the Jaynes-Cummings Model to the Dressed Atom and Cavity QED, Serge Haroche; *Collège de France, France.* Not available.

M1.4 • 09:30 am Invited
J-C Theory Out of the Box, Joseph H. Eberly; *Univ. of Rochester, USA.* Not available.

M1.5 • 09:45 am Invited
J-C Theory with Radiation Reaction: Neoclassical Theory, Carlos Stroud; *Univ. of Rochester, USA.* The Jaynes-Cummings paper treats the problem of one-atom interacting with one cavity mode with two alternative theories: quantum electrodynamics and semiclassical theory, and compares the predictions. The semiclassical theory was later extended to treat a single atom in free space interacting with a classical field including radiation reaction. The resulting theory was called Neoclassical theory, and is described by nonlinear optical Bloch equations. These nonlinear equations have shown up in a number of physical systems and were the subject of the famous Jaynes-Franken bet that was a prominent feature of the early Rochester Coherence and Quantum Optics Conferences. We will touch on all of these topics in a historical review.

10:00 am -- 10:30 am • Coffee Break, *Munnerlyn Atrium*

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and click on - **Access digest papers**
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Sloan Auditorium

10:30 am -- 12:00 pm
M2A • Session M2A
Chair: To be Announced

M2A.1 • 10:30 am Invited
Topological regularities of scalar/vector singular dynamic speckle fields, Marat S. Soskin, Vasyl Vasil'ev; *Inst. of Physics National Academy of Sciences of Ukraine, Ukraine.* Speckle fields of any complexity develop through loop/chain topological reactions. The sign paradox for singularities in vector speckle fields was installed and resolved.

M2A.2 • 11:00 am Invited
Topological Reactions in Optical Correlation Functions, Taco Visser; *Delft Univ. of Technology, Netherlands.* Not available

M2A.3 • 11:30 am Invited
Discovering Monstars: Unveiling New Coherent-optical Landscapes of Polarization, Amplitude and Phase , Enrique J. Galvez, Brett L. Rojec, Xinru Cheng; *Colgate Univ., USA.* We study new spatial-polarization modes with space variant polarization. We do so by preparing tailored optical beams bearing polarization in Poincare modes. We present the production of an asymmetric type of polarization-singularity C-points, known as monstars. This type of C-point can be produced by the superposition of two beams, one with an asymmetric optical vortex, and a second one with in a fundamental Gaussian mode, both in orthogonal circular polarization states.

Landers Auditorium

10:30 am -- 12:00 pm
M2B • Session M2B
Chair: To be Announced

M2B.1 • 10:30 am Invited
Knitting Entanglement: Assembling Photonic States with Delay Lines, Eli Megidish, Hagai S. Eisenberg; *Racah Inst. of Physics, Hebrew Univ. of Jerusalem, Israel.* The generation of multiphoton entanglement conventionally requires large amounts of resources. We present several efficient schemes for generating multiphoton graph states using only one source of single or entangled pairs of photons and delay lines.

M2B.2 • 11:00 am Invited
Recent Experiments on Quantum Network with Photons and Atoms, Jian-Wei Pan; *USTC, China.* In this talk I will present some recent experiments from our group, including eight-photon entanglement, topological quantum error-correction, quantum repeater and efficient and long-lived quantum memory, and entanglement distribution and quantum teleportation over 100km-scale free-space quantum channels. These experiments show the promising future possibility towards scalable quantum network with photons and atoms.

M2B.3 • 11:30 am Invited
Quantum-enhanced optical phase tracking, Howard M. Wiseman; *Griffith Univ., Australia.* We surpass the coherent-state limit to optical phase tracking using a CW phase-squeezed beam. Our phase varies stochastically over a wide range and consequently the best precision is achieved for a finite degree of squeezing.

12:00 pm -- 1:30 pm • Lunch Break, *Meliora Ballroom*

Hoyt Auditorium
1:30 pm -- 2:15 pm
M3 • Session M3
Presider: To be Announced

M3.1 • 1:30 pm Tutorial **[Sponsored by Contemporary Physics]**
Atomic physics and quantum optics using superconducting circuits, Franco Nori[1,2], J. Q. You[3]; *[1]RIKEN, Japan; [2]Univ. of Michigan, USA; [3]Beijing Computational Science Research Center, China.* Superconducting circuits [1-11] based on Josephson junctions exhibit macroscopic quantum coherence and can behave like artificial atoms. Recent technological advances have made it possible to implement atomic-physics and quantum-optics experiments on a chip using these artificial atoms. This pedagogical talk presents a brief introduction to this rapidly advancing field. We not only discuss phenomena analogous to those in atomic physics and quantum optics with natural atoms, but also highlight those not occurring in natural atoms.

2:15 pm -- 2:30 pm • Coffee Break, *Munnerlyn Atrium*

Sloan Auditorium

2:30 pm -- 4:00 pm
M4A • Session M4A
Presider: To be Announced

M4A.1 • 2:30 pm Invited
Strongly interacting photons in quantum nonlinear medium, Mikhail Lukin; *Harvard Univ., USA.* The realization of strong nonlinear interactions between individual light quanta (photons) is a long-standing goal in optical science and engineering, being of both fundamental and technological significance. We describe and demonstrate a medium that is nonlinear at the level of individual quanta, exhibiting strong absorption and phase shift for photon pairs while remaining transparent to single photons. The quantum nonlinearity is obtained by coherently coupling slowly propagating photons to strongly interacting atomic Rydberg states in a cold, dense atomic gas. Finally, we will discuss our progress towards realization of integrated quantum photonic systems, based on deterministic coupling of individual atoms and atom-like systems to photonic crystal cavities.

M4A.2 • 3:00 pm Invited
Dark solitons in quasi one dimensional Bose gas, Kazimierz M. Rzazewski[1], Mariusz Gajda[2,1], Miroslaw Brewczyk[3,1], Piotr Deuar[2], Przemyslaw Bienias[1], Krzysztof Pawlowski[1], Emilia Witkowska[2], Tomasz Karpiuk[3]; *[1]Center for Theoretical Physics, Polish Academy of Sciences, Poland; [2]Inst. of Physics, Polish Academy of Sciences, Poland; [3]Physics Dept., Univ. of Bialystok, Poland.* Dark solitons were created experimentally in quasi one dimensional Bose gas by external forces. We shall discuss two other cases of soliton formation: one is in rapidly cooled gas, the other is a spontaneous presence of solitons in the gas at thermal equilibrium.

Landers Auditorium

2:30 pm -- 4:00 pm
M4B • Session M4B
Presider: To be Announced

M4B.1 • 2:30 pm Invited
Wiring up Quantum Systems: Circuit QED with Artificial Atoms and Microwave Photons, Steven Girvin; *Office of the Provost, Yale Univ., USA.* A revolution is underway in the construction of 'artificial atoms' out of superconducting electrical circuits. 'Circuit QED' permits strong-coupling nonlinear optics at the single-photon level and gives an architecture for novel quantum information processing.

M4B.2 • 3:00 pm Invited
Quantum Optics with Many-Bod States, Mackillo Kira; *Philipps-Univ. Marburg, Germany.* Theoretical framework of quantum-optical spectroscopy is presented and applied to detect new many-body states and their quantum kinetics.

Sloan Auditorium	Landers Auditorium

2:30 pm -- 4:00 pm
M4A • Session M4A *(cont.)*
Presider: To be Announced

M4A.3 • 3:30 pm Invited
A priori light-matter entanglement using Rydberg atoms: towards truly functional quantum networks, Alexander M. Kuzmich; *Georgia Inst. of Technology, USA.* Truly functional quantum networks can be based on entanglement between light fields and optical collective excitations of an ultra-cold atomic gas created by deterministic Rydberg-level atomic interactions. Ultra-cold atoms are confined in an optical lattice with the same trapping potential for both the ground and the Rydberg atomic levels. The achieved separation of the external and internal atomic degrees of freedom is employed to entangle an optical atomic coherence and a light wavepacket, unconditionally, a priori, paving the way for

2:30 pm -- 4:00 pm
M4B • Session M4B *(cont.)*
Presider: To be Announced

M4B.3 • 3:30 pm Invited
Photonic Quantum Simulators: from Anderson Localization to Topological Insulators, Mordechai Segev; *Technion, Israel.* Many fundamental concepts are common to quantum systems and classical light. I will describe the recent progress in several topics, ranging from Anderson localization and hyper-transport to photonic graphene and photonic topological insulators.

4:00 pm -- 4:30 pm • Coffee Break , *Munnerlyn Atrium*

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Sloan Auditorium	Landers Auditorium

4:30 pm -- 6:00 pm
M5A • Session M5A
Presider: To be Announced

M5A.1 • 4:30 pm Invited
100% Correlation of Chaotic-thermal Light and Turbulence-Free Imaging, Yanhua Shih; *Dept. of Physics, Univ. of Maryland Baltimore County, USA.* This talk reports a recent experimental observation of intensity and intensity-fluctuation correlation and anti-correlation of chaotic-thermal light with 100% contrast. Based on this study, a novel technology of turbulence-free imaging has been developed.

M5A.2 • 5:00 pm Invited
Quantum Correlations from Classical Coherence Theory?, Daniel F. James[1,2]; [1]*Physics, Univ. of Toronto, Canada;* [2]*CQIQC, Univ. of Toronto, Canada.* This talk will describe recent research on different types of bi-partite classical and quantum correlations, and an approach based on notions of classical coherence theory that yields some interesting insights.

M5A.3 • 5:30 pm Invited
Quantum Tools for Classical Coherence, Ayman Abouraddy; *Univ. of Central Florida, USA.* The statistical description of optical fields in coherence theory is based on underlying fluctuations originating at the source or during propagation through a random medium. We show that uncertainty (partial coherence) also stems from the act of ignoring a degree of freedom of a beam when observing another degree of freedom classically entangled with it. Specifically, we demonstrate that Bell's measure, commonly used in tests of quantum non-locality, is as a quantitative tool that delineates intrinsic incoherence associated with statistical fluctuations from classical entanglement-based incoherence. This demonstrates, more generally, the applicability of concepts from quantum information processing to classical optical coherence theory and optical signal processing.

4:30 pm -- 6:00 pm
M5B • Session M5B
Presider: To be Announced

M5B.1 • 4:30 pm Invited
Optical Interactions with Quantum Dot Spins, Mete Atature; *Cambridge Univ., UK.* Quantum optics is immensely powerful in revealing essential physics of solid-state systems and further provides the opportunity to control its constituents, such as electronic and nuclear spins. I will discuss progress for semiconductor quantum dots.

M5B.2 • 5:00 pm Invited
Cavity quantum electrodynamics with semiconductor quantum dots, Olivier Gazzano[1], Anna Nowak[1], Christophe Arnold[1], Marcelo Almeida[2], Steffen Michaelis de Vasconcellos[1], Sinmone Luca Portalupi[1], Elisabeth Galopin[1], Andrew G. White[2], Isabelle Sagnes[1], Aristide Lemaitre[1], Loic Lanco[1], Pascale Senellart[1]; [1]*CNRS-Laboratoire de Photonique et de Nanostructures, France;* [2]*Univ. of Queensland, Australia.* By deterministically controlling the spontaneous emission of a single semiconductor quantum dot in a cavity, we fabricate ultrabright solid state sources of quantum light and devices presenting optical non-linearities at the few photon scale.

M5B.3 • 5:30 pm Invited
A Spin Qubit Coupled to a Photonic Crystal Cavity, Timothy M. Sweeney[1], Samuel G. Carter[2], Mijin Kim[3], Chul S. Kim[2], Dmitry Solenov[1], Sophia E. Economou[2], Thomas L. Reinecke[2], Lily Yang[1], Allan S. Bracker[2], Daniel Gammon[2]; [1]*NRC postdoctoral associate residing at the Naval Research Lab, USA;* [2]*Naval Research Lab, USA;* [3]*Sotera Defense Solutions, Inc., USA.* We developed a charge-controlled quantum dot coupled to a photonic crystal cavity. We charge the dot with a single electron and perform optical spin initialization, rotation and measurement, demonstrating a spin qubit coupled to a cavity.

6:30 pm — 7:30 pm • Dinner, *Meliora Ballroom*

May Room
7:30 pm -- 10:00 pm
M6 • CQO Poster Session

M6.01
A Study of Optically Levitated NV Centers, Levi Neukirch[1], Jan Gieseler[2], Romain Quidant[2,3], Lukas Novotny[4,5], Nick Vamivakas[4]; [1]*Dept. of Physics and Astronomy, Univ. of Rochester, USA;* [2]*ICFO-Institut de Ciencies Fotoniques, Spain;* [3]*ICREA-Institució Catalana de Recerca i Estudis Avançats, Spain;* [4]*Inst. of Optics, Univ. of Rochester, USA;* [5]*Photonics Lab., ETH Zürich, Switzerland.* We present nitrogen vacancy photoluminescence measurements from a nanodiamond levitated in a free-space optical-dipole trap. Photoluminescence decreases as trap laser power increases, and modulating the trap laser results in changes in the defect charge state.

M6.02
Amplification of Optical Pulse Delays using Weak Measurements, Mohammad Mirhosseini[1], Omar S. Magana Loaiza[1], Mehul Malik[1], Robert W. Boyd[2,1]; [1]*The Inst. of Optics, Univ. of Rochester, USA;* [2]*Physics, Univ. of Ottawa, Canada.* A novel scheme for super-sensitive measurement of optical pulse delays is proposed based on the concept of weak-value amplification. We discuss an experimental implementation of this technique utilizing a Mach-Zehnder interferometer.

M6.03
Bell Violation with Classical Non-determinism, Xiao-Feng Qian, Joseph H. Eberly; *Univ. of Rochester, USA.* We present some preliminary results of our current research on Bell violation with purely classical non-deterministic thermal light. Our analysis clarifies some mis-impressions among the terms: quantum mechanics, entanglement and Bell violations.

M6.04
Bell test of discrete-continuous entanglement, Xiao-Feng Qian, Curtis J. Broadbent, Joseph H. Eberly; *Univ. of Rochester, USA.* We report a summary of our recent work proposing a new Bell test for discrete-continuous entangled systems when the continuous variable state is unknown (i.e., arbitrary and inaccessible to direct measurements).

M6.05
Bimodal Hong-Ou-Mandel Interference in Symmetric and Asymmetric Optical Systems, Cody C. Leary, Thomas Gilliss, Deepika Sundarraman; *College of Wooster, USA.* We investigate Hong-Ou-Mandel interference in symmetric and asymmetric interferometers, with the input photons prepared in arbitrary first-order spatial modes. We find that Hong-Ou-Mandel interference may occur in conjunction with mode transformation, and between distinguishable inputs.

M6.06
Bound State Influence on Long-Time Non-Exponential Decay in Open Quantum Systems, Savannah Garmon; *Inst. of Industrial Science, Univ. of Tokyo, Japan.* For a discrete system attached to a continuum, a bound state gives rise to two long-time dynamical regions: a near-asymptotic region of t^(-1) decay and a fully asymptotic region of t^(-3) decay.

M6.07
Broadband QED using Hyperbolic Metamaterials, Vinod M. Menon[1,2], Harish Krishnamoorthy[1,2], Zubin Jacob[3], Evgenii Narimanov[4], Ilona Kretzschmar[5]; [1]*Physics, CUNY Queens College, USA;* [2]*Physics, CUNY Graduate Center, USA;* [3]*Electrical and Computer Engineering, Univ. of Alberta, Canada;* [4]*Electrical and Computer Engineering, Purdue Univ., USA;* [5]*Chemical Engineering, CUNY - City College, USA.* We demonstrate broadband (30nm) enhancement of spontaneous emission from quantum dots placed in the near-field of hyperbolic metamaterials. The appearance of large wave-vector states in the hyperbolic dispersion regime is responsible for the observed effect.

M6.08
Classical Entanglement in Electromagnetic Beams, Kumel Kagalwala[1], Giovanni Di Giuseppe[1,2], Ayman Abouraddy[1], Bahaa Saleh[1]; [1]*CREOL, College of Optics and Photonics, Univ. of Central Florida, USA;* [2]*Physics Division, School of Science and Technology, Univ. of Camerino, Italy.* We study classical entanglement for an optical beam with two binary degrees of freedom: polarization and spatial parity; and demonstrate experimentally a measurement of Bell's inequality and show its usefulness as a quantitative tool in classical optical coherence theory.

M6.09
Coherence Measurements from Two-Dimensional Binary Phase Masks: Theory and Experimental Results, Seongkeun Cho[2], Katelynn Sharma[1], Miguel Alonso[1], Thomas Brown[1]; [1]*Inst. of Optics, Univ. of Rochester, USA;* [2]*Mechanical Engineering, Massachusetts Inst. of Technology, USA.* A simple scheme is implemented for the measurement of spatial coherence of partially coherent fields using a two dimensional binary phase mask. Initial results indicate our methods are reliable for certain types of beams.

M6.10
Coherent Interaction of a Single Emitter with a Metallic Structure, Xuewen Chen[1], Andreas Maser[1], Benjamin Gmeiner[1], Stephan Goetzinger[1], Mario Agio[2], Vahid Sandoghdar[1]; [1]*Max Planck Inst. for the Science of Light and Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany;* [2]*National Inst. of Optics (INO-CNR) and European Lab. for Nonlinear Spectroscopy (LENS), Italy.* We report on theoretical and experimental studies on coherent spectroscopy of a single emitter coupled to a metallic structure. We demonstrate that the emitter can either enhance absorption by 1000 times or cloak the structure.

M6.11
Collective Spontaneous Emission and Tripartite Entanglement of Driven, Damped Atoms in Free Space, Ethan Stanifer[1], James Clemens; *Dept. of Physics, Miami Univ., USA.* We calculate the bipartite and tripartite entanglement of three damped two-level atoms in free space with one atom driven. There are two sources of the entanglement: dipole-dipole coupling and collective spontaneous emission.

M6.12
Compact 2D Nonlinear Photonic Crystal source of Beamlike Path Entangled Photons, Eli Megidish[1], Assaf Halevy[1], Hagai S. Eisenberg[1], Ayelet Ganany-Padowicz[2], Nili Habshoosh[2], Ady Arie[2]; [1]*Physics, Racah Inst. of Physics, Hebrew Univ. of Jerusalem, Israel;* [2]*School of Electrical Engineering, Fleischman Faculty of Engineering, Tel Aviv Univ., Israel.* We experimentally demonstrate a compact two-photon path entanglement source based on 2D nonlinear quasi phase matching technique. Photon pairs are directly generated into well defined and easy to collect non-collinear beamlike modes.

M6.13
Control of Two-Photon Absorption using Phase-Modulated Collinear Type-I Degenerate Parametric Down-Conversion, Andrea T. Joseph, Roger Andrews; *Univ. of the West Indies (System), Trinidad and Tobago.* We demonstrate control over the two-photon absorption of collinear type-I down-converted photons that have been phase-modulated. We find that absorption can be enhanced and suppressed using the modulation frequency and detuning parameters.

M6.14
Demonstration of the Quantum Response to Loss with Ultra-Broadband Bi-Photons Interference, Avi Pe'er, Yaakov Shaked; *Bar-Ilan Univ., Israel.* By using an ultra-broad (100THz) bi-photon source and a pairwise interferometer, we measure the bi-photons spectral phase and amplitude, and demonstrate the quantum dependence of the interference contrast on internal loss.

M6.15
Observing the Transition from Classical to Quantum Photon Correlation in Four Wave Mixing, Rafi Z. Vered, Yelena Ben-Or[1], Michael Rosenbluh[1], Avi Pe'er; *Physics Dept. and BINA center for Nano-technology, Bar-Ilan Univ., Israel.* We demonstrate two-photon interference with bi-photons produced by FWM. We explore the quantum / classical nature of the light by observing the loss dependence of the interference contrast at various intensities across the quantum-to-classical transition.

M6.16
Direct Measurement of a 27-Dimensional Quantum State, Mehul Malik[1], Mohammad Mirhosseini[1], Martin Lavery[2], Jonathan Leach[3,4], Miles J. Padgett[2], Robert W. Boyd[1,4]; [1]*The Inst. of Optics, Univ. of Rochester, USA;* [2]*School of Physics and Astronomy, Univ. of Glasgow, UK;* [3]*School of Engineering and Physical Sciences, Heriot-Watt Univ., UK;* [4]*Dept. of Physics, Univ. of Ottawa, Canada.* We show the experimental direct measurement of a high-dimensional quantum state in the discrete orbital-angular-momentum (OAM) basis. Our technique employs weak measurements of OAM and strong measurements of angular position.

M6.17
Direct measure of the Schmidt number of biphotons, Andrea Cavanna; *Max-Planck-Gesellschaft, Germany.* We implement a method to assess the transverse entanglement of biphotons in both modulus and phase of the quantum state. This is achieved by an interferometric measurement of the Schmidt number which is a universal quantifier for entanglement.

M6.18
Dissipative dynamics of the Rabi model in the quasi-degenerate qubit and ultra-strong coupling regime, Shantanu Agarwal, Seyed Mohammad Hashemi Rafsanjani, Joseph H. Eberly; *Univ. of Rochester, USA.* We study the dissipative dynamics of a coupled qubit-oscillator system. We restrict our analysis to the quasi-degenerate qubit and ultra-strong coupling regime.

M6.19
Effects of Phase Fluctuations on the Sensitivity of NOON State in a Noisy Environment, Bhaskar Roy Bardhan, Jonathan P. Dowling; *Louisiana State Univ., USA.* We study effects of phase fluctuations on NOON state's sensitivity in presence of realistic noise. Phase sensitivity is investigated with parity detection and calculated quantum Fisher information shows lower bound saturates quantum Cramer-Rao bound.

M6.20
Effects of Reflection and Refraction on Spatial Coherence of an Electromagnetic Beam, Mayukh Lahiri[1], Emil Wolf[1,2]; [1]*Physics and Astronomy, Univ. of Rochester, USA;* [2]*Inst. of Optics, Univ. of Rochester, USA.* We study the change in spatial coherence of an electromagnetic beam on reflection and refraction. The results are obtained by applying the recently developed theory of refraction and reflection of a partially coherent beam.

M6.21
Enhanced Phase Estimation using Quantum and Classical Light, Yonatan Israel; *Weizmann Inst. of Science, Israel.* We show that by mixing quantum spontaneous parametric down-conversion with the classical coherent state we can enhance phase sensitivity in an interferometer, under experimental considerations of photon loss and non ideal detection.

M6.22
Enhancement of Entanglement Between Coupled Quantum Dots in a Cavity Driven by Modulating Field, Hsiao-harng Shiau[1], Arnab Mitra[1,2], Reeta Vyas[1]; [1]*Dept. of Physics, Univ. of Arkansas, USA;* [2]*Dept. of Physics, Florida State College, USA.* We show that by modulating the field driving a cavity with two coupled quantum dots in the presence of cavity and dot decays, can periodically generate much larger entanglement than the maximum steady-state value.

M6.23
Entanglement Dynamics in the Presence of Unital Noisy Channels, Assaf Shaham, Assaf Halevy, Liat Dovrat, Eli Megidish, Hagai S. Eisenberg; *Hebrew Univ. of Jerusalem, Israel.* The entanglement level of two initially entangled qubits, subjected to an uncorrelated unital noisy channel is simply manifested by the radii of its Bloch sphere mapping. We demonstrate this relation experimentally using an all-optical setup.

M6.24
Experimental generation of an optical field with arbitrary spatial coherence properties, Brandon V. Rodenburg[1], Mohammad Mirhosseini[1], Omar S. Magaña-Loaiza[1], Robert W. Boyd[1,2]; [1]*Inst. of Optics, Univ. of Rochester, USA;* [2]*Physics, Univ. of Ottawa, Canada.* We describe an experimental technique to generate a quasi-monochromatic field with any arbitrary spatial coherence described by the cross-spectral density function, W(r1,r2).

M6.25
Experimental observation of quantum correlations in modular variables, Marcos D. Carvalho[1], José Ferraz[1], Gilberto F. Borges[1], Pierre L. de Assis[1,2], Sebastião Pádua[1], Stephen P. Walborn[3]; [1]*Departamento de Física, Universidade Federal de Minas Gerais, Brazil;* [2]*Inst. Néel, Centre National de la Recherche Scientifique et Université Joseph Fourier, France;* [3]*Instituto de Física, Universidade Federal do Rio de Janeiro, Brazil.* We experimentally detect entanglement in modular position-momentum variables of down-converted photon pairs which have passed through D-slit apertures. We employ two entanglement criteria, one using variances of the modular variables, the other using the Shannon entropy.

M6.26
Frequency cavity pulling induced by a single semi-conducting artificial atom, Alexia Auffeves[1], Daniel Valente[1], Jan Suffczynski[2,3], Tomasz Jakubczyk[3], Adrien Dousse[2], Aristide Lemaitre[2], Isabelle Sagnes[2], Loic Lanco[2], Paul Voisin[2], P. Senellart[2]; [1]*Institut Neel - CNRS, France;* [2]*LPN - CNRS, France;* [3]*Univ. of Warsaw, Poland.* An artificial atom coupled to a resonator of narrower emission linewidth opens a whole new field for quantum electrodynamics : we investigate such regime and evidence spectacular cavity pulling induced by a single quantum dot.

M6.27
Increasing The Giant Kerr Effect By Narrowing The EIT Window Beyond The Signal Bandwidth, Greg Dmochowski, Amir Feizpour, Alex Hayat, Matin Hallaji, Chao Zhuang, Aephraim M. Steinberg; *Univ. of Toronto, Canada.* We experimentally show that giant EIT-based Kerr nonlinearities continue to benefit from narrowing the EIT window even as the signal bandwidth comes to exceed this transparency width

M6.28
Interaction-free measurements with electrons, Sebastian Thomas[1], Peter Hommelhoff[1,2]; [1]*Max Planck Inst. of Quantum Optics, Germany;* [2]*Physik-Dept., Universität Erlangen-Nürnberg, Germany.* We discuss general features of interaction-free measurements with electrons. In particular, we investigate the effect of semi-transparent samples using a numerical simulation of the Schrödinger equation.

M6.29
Localized Laser Structures in Coupled Semiconductor Micro-resonators, Patrice Genevet[1,3], Margherita Turconi[1], Mathias Marconi[1], Stéphane Barland[1], Massimo Giudici[1], Jorge Tredicce[1,2]; [1]*Institut Non Linéaire de Nice, Université de Nice Sophia Antipolis, Centre National de la Recherche Scientifique, France;* [2]*Pole Pluridisciplinaire de la Matiere et de l'Environnement, Université de la Nouvelle Caledonie, New Caledonia;* [3]*School of Engineering and Applied Sciences, Harvard Univ., USA.* We show existence of Localized Laser Structures (LLS) in two coupled semiconductor microresonators. LLS generate from spontaneous emission noise as independent lasers without any driving field. The phase invariance leads to exotic LLS, as localized vortices.

M6.30
Long-lived ion qubits in a microfabricated trap for scalable quantum computation, So-Young Baek[1], Emily Mount[1], Peter Maunz[2], Stephen Crain[1], Daniel Gaultney[1], Rachel Noek[1], Jungsang Kim[1]; [1]*Duke Univ., USA;* [2]*Sandia National Laboratories, USA.* We report state detection, single qubit coherent operations and Raman sideband cooling to near the motional ground state by trapping a single 171Yb+ ion in a surface trap designed and fabricated at Sandia National Laboratories.

M6.31

Measurements with on-off detector systems, Jan Sperling[1], Werner Vogel[1], Girish S. Agarwal[2]; *[1]Dept. of Physics, Univ. of Rostock, Germany; [2]Dept. of Physics, Oklahoma State Univ., USA.* We study systems of on-off detectors. For coherent light, such kinds of measurements reveal a binomial statistics rather than a Poisson one. Hence, nonclassicality may be determined by a sub-binomial click statistics.

M6.32

Mode-selective all-optical switching via quantum frequency conversion, Abijith Kowligy, Prem Kumar, Yu-Ping Huang; *EECS Dept., Northwestern Univ., USA.* We propose mode-selective all-optical switching by utilizing quantum frequency conversion in a single-mode regime. This can potentially augment existing tools for all-optical information processing in the quantum domain.

M6.33

Observation of non-diffracting behavior at the single-photon level, Héctor Cruz-Ramírez[1], Roberto Ramírez-Alarcón[1,2], Francisco J. Morelos[1], Pedro A. Quinto-Su[1], Julio C. Gutiérrez-Vega[3], Alfred B. U'Ren[1]; *[1]Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico; [2]División de Ciencias e Ingeniería, Universidad de Guanajuato, Mexico; [3]Photonics and Mathematical Optics Group, Tecnológico de Monterrey, Mexico.* We demonstrate the generation of non-diffracting heralded single photons produced by SPDC when the crystal is pumped by a Bessel-Gauss beam. The non-diffracting photons are produced without the need for any post-generation projection

M6.34

Optical Bistability beyond Rotating Wave Approximation, S. S. Hassan[1], Amitabh Joshi[2], Y. A. Sharaby[3]; *[1]Dept. of Math, Univ. of Bahrain, Bahrain; [2]Dept. of Phys, EIU, USA; [3]Dept. of Phys, Suez Canal Univ., Egypt.* Optical bistable device consisting of two-level atomic system inside a ring cavity beyond rotating wave approximation offers the physical possibility of generating ultra-weak first harmonic signal and the simultaneous opposite coding of the information.

M6.35

Optical microscopy at the sub-nano scale via coherent population oscillations, Kishor T. Kapale[1], Wa Kun Lam[2], Girish S. Agarwal[2]; *[1]Dept. of Physics, Western Illinois Univ., USA; [2]Dept. of Physics, Oklahoma State Univ., USA.* We present methods for microscopy beyond the Rayleigh limit through the phenomena of coherent population oscillations. The atomic fluorescence shows sharp spatial features offering resolution below one nanometer using spatially shaped pump and probe beams.

M6.36

Path-Symmetric States and Parity Detection in Quantum Optical Interferometry, Kaushik P. Seshadreesan[1], Sejong Kim[2], Bhaskar Roy Bardhan[1], Jonathan P. Dowling[1], Hwang Lee[1]; *[1]Physics & Astronomy, Louisiana State Univ., USA; [2]Mathematics, Lousiana State Univ., USA.* In optical phase estimation, pure states that achieve maximal phase sensitivities with number counting, are symmetric with respect to a certain exchange of paths. We prove the optimality of photon-number parity detection for such path-symmetric states.

M6.37

Photon Number Distributions From a Diode Laser, Marc Assmann[1], Georgios Roumpos[1], Steven T. Cundiff[1]; *[1]JILA, Univ. of Colorado & National Inst. of Standards and Technology, USA.* We use balanced homodyne detection to extract photon number distributions of diode laser light as the laser crosses threshold. We compare the results to the semiclassical singlemode laser model, and characterize the excess noise.

M6.38

Polarization and Propagation Characteristics of Laser Beams, Jessica Conry, Reeta Vyas, Surendra Singh; *Dept. of Physics, Univ. of Arkansas, USA.* Polarization of laser beams and its evolution with propagation is studied theoretically. The presence of cross-polarization component for linearly polarized Hermite-Gauss and Laguerre-Gauss family of laser beams is demonstrated experimentally.

M6.39

Propagation of a bipartite entangled state through a fast-light medium, Jeremy Clark, Ryan Glasser, Quentin Glorieux, Ulrich Vogl, Paul D. Lett; *National Inst. of Standards & Technology, USA.* We generate entangled twin beams using four-wave-mixing and investigate the behavior of the quantum correlations when one field is sent through a fast-light medium with anomalous dispersion. We report an advance of 3.7±0.1 ns, marking the realization of a negative temporal delay line for quantum states.

May Room
7:30 pm -- 10:00 pm
M6 • CQO Poster Session *(cont.)*

M6.40
Quantum Coherence Effects in Plasmonics: New Dimension in Nanophotonics, Pankaj K. Jha[1], Xiaobo Yin[1,2], Xiang Zhang[1,2]; [1]*Mechanical Engineering, Univ. of California, USA;* [2]*Materials Science Division, Lawrence Berkeley National Lab., USA.* We present theoretical demonstration of quantum coherence-enhanced propagation of surface plasmon polaritons(SPPs). We show that propagation dynamics of SPPs can benefit from the quantum boost in the visible regime, adding a new dimension to nanophotonics.

M6.41
Quantum Dot Spin-Photon Entanglement, John Schaibley[1], Alex P. Burgers[1], Gregory A. McCracken[1,4], Luming Duan[1], Paul R. Berman[1], Duncan G. Steel[1], Allan S. Bracker[2], Daniel Gammon[2], Lu J. Sham[3]; [1]*The H. M. Randall Lab. of Physics, Univ. of Michigan, USA;* [2]*Naval Research Lab., USA;* [3]*Dept. of Physics, Univ. of California, San Diego, USA;* [4]*Dept. of Applied Physics, Stanford Univ., USA.* Single electron spins confined to InAs quantum dots (QDs) can serve as qubits for quantum information applications. We report QD spin-photon entanglement useful for scaling a QD spin architecture via intermediate photonic qubits.

M6.42
Quantum Secure Direct Communication, Gui Lu Long[1,2]; [1]*Stare key Lab for Low-dimensional Quantum Physics and Dept. of Physics, Tsinghua Univ., China;* [2]*Tsinghua National Lab. for Information Science and Technology, Tsinghua Univ., China.* Quantum secure direct communication transmits secret messages directly without another classical transmission. We describe its principle and working procedure through example protocols. Distinctions from QKD are pointed out, and its wide applications are given

M6.43
Role of Phase Matching on the Generation of Squeezed States of Light with Four-Wave Mixing, Alberto M. Marino[1], Matthew T. Turnbull[2], Plamen G. Petrov[2], Christopher S. Embrey[2], Vincent Boyer[2]; [1]*Univ. of Oklahoma, USA;* [2]*Univ. of Birmingham, UK.* We perform theoretical and experimental studies of the effect of phase matching on the generation of entangled twin beams with four-wave mixing. We find that it plays a critical role on the optimum parameters for the process.

M6.44
Semiclassical entanglement analyses in a non-degenerate parametric oscillator (NDPO), Daniel B. Erenso[1], Jordan Dodson[1], Fesseha Kassahun[2]; [1]*Physics & Astronomy, Middle Tennessee State Univ., USA;* [2]*Physics, Addis Ababa Univ., Ethiopia.* The entanglement of the intracavity photons in subthreshold NDPO coupled to a squeezed vacuum is studied using the von-neumann entropy (VNE). The VNE is calculated in terms of the Q-function representation for the density operator.

M6.45
Sensitive estimation of angular displacements using weak measurements, Omar S. Magana Loaiza[1], Mohammad Mirhosseini[1], Brandon Rodenburg[1], Robert W. Boyd[1,2]; [1]*The Inst. of Optics, Univ. of Rochester, USA;* [2]*Dept. of Physics, Univ. of Ottawa, Canada.* We demonstrate an experimental method that allows for sensitive measurements of angular position of light using weak value amplification. This offers an alternative to previously established methods that use nonclassical light for angular displacement estimation.

M6.46
Single-Photon Source with Asymmetric Multiplexed Architecture, Luca Mazzarella[1], Francesco Ticozzi[1,2], Alexander V. Sergienko[3], Giuseppe Vallone[1], Paolo Villoresi[1]; [1]*Univ. of Padova, Italy;* [2]*Dartmouth College, USA;* [3]*Boston Univ., USA.* The asymmetric configuration of multiplexed heralded single photon sources is introduced and shown to outperform the faint laser source. This design points out the potential use for integrated implementation of high performance single photon source.

M6.47
Single-photon nonlinear optics in passive photonic nanocavities, Dario Gerace; *Dipartimento di Fisica, Università degli Studi di Pavia, Italy.* It is shown that strong enhancement of native optical nonlinearities in photonic resonators made of ordinary nonlinear materials can lead to single-photon emission via photon blockade of a resonant driving laser. A theoretical characterization is given by means of the second-order correlation function as the main figure of merit.

M6.48
Sunlight can not be viewed as a series of random ultra-fast pulses, Agata Branczyk[1], Aurelia Chenu[1], Gregory D. Scholes[1], John E. Sipe[2]; [1]*Dept. of Chemistry, The Univ. of Toronto, Canada;* [2]*Dept. of Physics, The Univ. of Toronto, Canada.* It has been suggested that sunlight can be viewed as a series of random ultra-fast pulses. We show that such a decomposition can not satisfy the properties of blackbody radiation.

M6.49

Super-Resolving Quantum Radar: Coherent-State Sources with Homodyne Detection Suffice to Beat the Diffraction Limit, Jonathan P. Dowling[1], Kebei Jiang[1], Hwang Lee[1], Christopher Gerry[2]; [1]*Physics and Astronomy, Louisiana State Univ., USA;* [2]*Physics and Astronomy, Lehman College, USA.* We show that coherent radar radiation sources, coupled with a quantum homodyne detection scheme, provide both longitudinal and angular super-resolution much below the Rayleigh diffraction limit, with sensitivity at the shot-noise limit.

M6.50

The Jaynes-Cummings Model in a Cross Cavity, Julio C. Garcia-Melgarejo[1], Jose J. Sánchez-Mondragón[1], Omar S. Magaña-Loaiza[2]; [1]*Depertamento de Óptica, Instituto Nacionaal de Astrofisica, Óptica y Electrónica, Mexico;* [2]*Departement of Physics and Astronomy, Univ. of Rocheser, USA.* In this work we describe a variation of the Jaynes-Cummings model for a two-level atom placed in a cross cavity. The interchange of photons between the cavities allows explore the generation of photon dark states.

M6.51

Time-domain Measurements of Single-Photon Tunneling Phenomena, Andreas C. Liapis[1], George M. Gehring[1], Svetlana G. Lukishova[1], Robert W. Boyd[1,2]; [1]*The Inst. of Optics, Univ. of Rochester, USA;* [2]*Dept. of Physics and School of Electrical Engineering and Computer Science, Univ. of Ottawa, Canada.* Using a Hong-Ou-Mandel interferometer, we have measured single-photon time delays in frustrated total internal reflection in a liquid-crystal-filled double-prism structure and in transmission through chiral photonic band gap liquid crystal structures with sub-fs resolution.

M6.52

Topological Phase Transitions in Photonic Quasicrystals, Mor Verbin[1], Yaacov E. Kraus[2], Oded Zilberberg[2], Yoav Lahini[1,3], Yaron Silberberg[1]; [1]*Dept. of Physics of Complex Systems, Weizmann Inst. of Science, Israel;* [2]*Dept. of Condensed Matter Physics, Weizmann Inst. of Science, Israel;* [3]*Dept. of Physics, Massachusetts Inst. of Technology, USA.* In this paper we present a direct observation of a topological phase transition between two topologically inequivalent quasicrystals, and prove the topological equivalence between two seemingly different quasicrystalline systems, the Harper and the Fibonacci quasicrystals.

M6.53

Transfer of quantum states in a four-qubit system, Smail Bougouffa[1], Zbigniew Ficek[2]; [1]*Dept. of Physics, Taibah Univ., Saudi Arabia;* [2]*NCMP, King Abdulaziz City for Science & Tech, Saudi Arabia.* The complete transfer of quantum states and entanglement mediated by either atoms or the overlapping cavity field modes in a four-qubit system composed of two single-mode cavities and two two-level atoms is discussed.

M6.54

Two-Dimensional Photonics with Molybdenum Disulfide, Kenneth Goodfellow[1], Ryan Beams[1], Lukas Novotny[1,2], Nick Vamivakas[1]; [1]*Univ. of Rochester, USA;* [2]*ETH Zürich, Switzerland.* We optically determine the thickness of molybdenum disulfide (MoS2) flakes by photoluminescence and Raman measurements. A transfer technique is demonstrated to pick and place MoS2 flakes on target structures.

M6.55

Using a Single Diamond NV Center for Nanoscale Fluorescence Lifetime Imaging, Ryan Beams[1], Dallas Smith[1], Timothy Johnson[2], Sang-Hyun Oh[2], Lukas Novotny[3,1], Nick Vamivakas[1]; [1]*Inst. of Optics, Univ. of Rochester, USA;* [2]*Electrical and Computer Engineering, Univ. of Minnesota, USA;* [3]*Photonics Lab., ETH Zurich, Switzerland.* We study the near-field optical properties of a diamond nanocrystal hosting a single NV center. Using a single NV center as a probe of the electromagnetic mode structure, we demonstrate nanoscale fluorescence lifetime imaging microscopy.

M6.56

Wide band optical switch via white light cavity, Mohammad D. Al-amri; *King Abdulaziz City for Science & Tech, Saudi Arabia.* Controlling reflectivity optically over a wide range of frequency band can be of great demand. We show how such a devise can be realized using a Fabry-Perot cavity filled with a three-level atomic gas.

M6.57

Witnessing of Multipartite Entanglement, Jan Sperling, Werner Vogel; [1]*Dept. of Physics, Univ. of Rostock, Germany.* We study the construction of witnesses for multipartite entanglement. This is done via the so-called multipartite separability eigenvalue equations. By its analytical solution, we identify high order multipartite entanglement in continuous variable systems.

May Room
7:30 pm -- 10:00 pm
M6 • CQO Poster Session *(cont.)*

M6.58
Spin-Nematic Squeezing, Non-Gaussian States, and Dynamical Stabilization of a Quantum Spin System, Corey Gerving[1,2]; [1]*Physics, Georgia Inst. of Technology, Atlanta, GA, USA.* [2]*Physics, USA; Military Academy, West Point, NY, USA.* Non-equilibrium spin-1 condensates are created by quenching through a quantum phase transition. Subsequent evolution generates 10 dB of spin-nematic squeezing and highly non-Gaussian states. Additionally, we demonstrate dynamical stabilization of the spin dynamics.

M6.59
Cavity Quantum Electrodynamics with Epitaxial Quantum Dots, Yiming Lai[1], Tanya Malhotra[1], Laura Kinnischtzke[1], Nick Vamivakas[2], Antonio Badolato[1]; [1]*Physics, Univ. of Rochester, Rochester, NY, USA;* [2]*Optics, Univ. of Rochester, Rochester, NY, USA.* We present theoretical and experimental results of quantum photonic devices based on photonics crystals in III-V semiconductors.

M6.60
Withdrawn

M6.61
Integrated Nanophotonics for Quantum Photonics Devices, Tanya Malhotra[1], Yiming Lai[1], Matteo Galli[2], Dario Gerace[2], Robert W. Boyd[1], Antonio Badolato[1]; [1]*Univ. of Rochester, Rochester, NY, USA;* [2]*Univ. of Pavia, Pavia, Italy.* Interferometry with 99% visibility is demonstrated in an integrated nanophotonics device based on photonic crystal circuitry in a GaAs slab. Such a device demonstrates an adaptable and robust platform to implement quantum photonics devices.

M6.62
Continuous Delay of Single Photons, Stéphane Clemmen, Alessandro Farsi, Alex Gaeta; *School of Applied and Engineering Physics, Cornell Univ., Ithaca, NY, USA.* We report the first demonstration of continuous delay imparted on single photons using a frequency conversion-dispersion technique. Our system shows tunable delays up to 300 ps with on/off efficiencies of 45% and a signal-to-noise ratio up to 5.

M6.63
The Phase Diagram of Polaritons in a Coupled One-Dimensional Array of Cavities Driven by a Laser with Non-Uniform Intensity, Abuenameh Aiyejina[1], Roger Andrews; *Physics, The Univ. of the West Indies, St. Augustine, Trinidad and Tobago.* The phase diagram and dynamics of a polaritonic, laser-driven, disordered Bose-Hubbard system are investigated. We employ the site-dependent Gutzwiller method and find the Bose-glass phase and a dependence on ramp time in the dynamics.

M6.64
Measuring the Gouy Phase of Matter Waves Using Full Bloch Bose-Einstein Condensates, Azure Hansen[1], Justin T. Schultz[2], Nick Bigelow[1,2]; [1]*Dept. of Physics and Astronomy, Univ. of Rochester, Rochester, NY, USA;* [2]*The Inst. of Optics, Univ. of Rochester, Rochester, NY, USA.* We propose and demonstrate experimental steps towards a new method for directly measuring the Gouy phase in a matter wave (Bose-Einstein condensate) system via an atomic analogy of full Poincare optical beams.

M6.65
Imaging Stokes Parameters of Spinor BECs, Justin T. Schultz[1], Azure Hansen[2], Nick Bigelow[1,2]; [1]*The Inst. of Optics, Univ. of Rochester, Rochester, NY, USA;* [2]*Dept. of Physics and Astronomy, Univ. of Rochester, Rochester, NY, USA.* We present two methods to image the spin density and relative phases of states in spinor BECs. In a psuedo-spin-1/2 system, these measurements are analogous to the Stokes parameters used to describe polarization in optics.

M6.66
Spin Textures and Topological Excitations in Spinor 87-Rb Bose-Einstein Condensates, Azure Hansen[1], Justin T. Schultz[2], Nick Bigelow[1,2]; [1]*Dept. of Physics and Astronomy, Univ. of Rochester, Rochester, NY, USA;* [2]*The Inst. of Optics, Univ. of Rochester, Rochester, NY, USA.* We engineer a variety of topological excitations in a BEC using a two-photon Raman process. Structures such as coreless vortices, fractional vortices, skyrmions, and monopoles can be created.

M6.67
Observation of On-Chip Optical Squeezing, Avik Dutt[1], Kevin Luke[1], Sasikanth Manipatruni[2], Alex Gaeta[1], Paulo A. Nussenzveig[3], Michal Lipson[1], [1]*Cornell Univ., Ithaca, NY, USA;* [2]*Intel Corporation, Hillsboro, OR, USA.* [3]*Universidade de São Paulo, Sao Paulo, Brazil.* We report the first demonstration of on-chip optical squeezing in a CMOS compatible integrated SiN ring resonator optical parametric oscillator operating above threshold. We measure 1.7 dB intensity-difference squeezing between bright signal and idler beams.

M6.68
Demonstration of N00N State Optical Centroid Measurement using an 11-detector Array, Dylan Mahler[1,2], James Bateman[1,2], Lee Rozema[1,2], Amir Feizpour[1,2], Ryo Okamoto[3,4], Alex Hayat[1,2], Aephraim M. Steinberg[1,2]; [1]*Centre for Quantum Information & Quantum Control and Inst. for Optical Sciences, Toronto, ON, Canada;* [2]*Physics, Univ. of Toronto, Toronto, ON, Canada;* [3]*Research Inst. for Electronic Science, Hokkaido Univ., Sapporo, Japan;* [4]*The Inst. of Scienctific and Industrial Research, Osaka Univ., Osaka, Japan.* We demonstrate optical super-resolution using a quantum centroid measurement of 2-photon N00N states, using a scalable 11-detector measurement scheme. We will also present the latest results from a 3-photon extension.

Hoyt Auditorium
08:30 am -- 10:00 am
T1 • Session T1
Presider: To be Announced

T1.1 • 08:30 am Invited
Nonlocal Interferometry Using Schrodinger Cats, James D. Franson; *Univ. of Maryland Baltimore County, USA.* A method for performing nonlocal interferometry using macroscopic phase-entangled coherent states is described. This allows Bell's inequality to be violated using Schrodinger cat states over relatively large distances in optical fibers.

T1.2 • 09:15 am Invited
Entangled Photons in Larger Real and Hilbert Spaces, Anton Zeilinger[1,2]; [1]*Univ. of Vienna, Austria;* [2]*Austrian Academy of Sciences, Austria.* These experiments are reported: quantum teleportation with feed-forward between Canary Islands, loophole-free Schrödinger steering, entanglement of 300 units angular momentum, entanglement in a 100-dimensional Hilbert space, and closing the fair-sampling loophole for photons.

10:00 am -- 10:30 am • Coffee Break, *Munnerlyn Atrium*

Sloan Auditorium

10:30 am -- 12:00 pm
T2A • Session T2A
Presider: To be Announced

T2A.1 • 10:30 am Invited
Demonstration of a State of Light with Purely Transverse Angular Momentum, Peter Banzer[1,2], Martin Neugebauer[1,2], Andrea Aiello[1,2], Christoph Marquardt[1,2], Norbert Lindlein[2], Thomas Bauer[1,2], Gerd Leuchs[1,2]; [1]*MPI for the Science of Light, Germany;* [2]*Inst. of Optics, Information and Photonics, Univ. Erlangen-Nuremberg, Germany.* We demonstrate and discuss a state of light with purely transverse angular momentum - a photonic wheel - generated by tight focusing of polarization tailored light. We use an experimental nanoprobing technique to measure the corresponding distribution.

T2A.2 • 11:00 am Invited
Optical Vortices in Discrete Rings, Anton Desyatnikov; *Australian National Univ., Australia.* We discuss the dynamics and topological transformations of discrete vortices in various rings of coupled nonlinear oscillators featuring Fano resonances, parity time symmetric defects, and coupled optical waveguides with positive and negative refractive indices.

T2A.3 • 11:30 am Invited
Assessing Higher-order Quantum Polarization Correlations using Multipole Expansions, Luis Sanchez-Soto; *Universidad Complutense, Spain.* We use a simple multipole expansion of the polarization density matrix. The resulting multipoles are used to construct quasiprobability distributions that appear as a sum of successive moments of the Stokes variables; the first one corresponding to the classical picture on the Poincaré sphere. In this way we formulate a whole hierarchy of measures that properly assess higher-order polarization correlations.

Landers Auditorium

10:30 am -- 12:00 pm
T2B • Session T2B
Presider: To be Announced

T2B.1 • 10:30 am Invited
Quantum Walks in Photonic Lattices: Tight Binding in a New Light, Yaron Silberberg; *Weizmann Inst. of Science, Israel.* Photons propagate in periodic and disordered lattices with minimal decoherence and with great control of initial states, displaying a rich spectrum of new phenomena and throwing light on a number of condensed matter effects.

T2B.2 • 11:00 am Invited
Two-photon interference from disparate quantum sources, Glenn Solomon[1], Edward B. Flagg[1], Sergey V. Polyakov, Tim Thomay, Alan Migdall; *Joint Quantum Inst., National Inst. of Standards & Technology, and Univ. of Maryland, USA.* When photons emitted from different sources are indistinguishable they will interfere when brought together on a beam splitter. Using quantum dots and parametric down conversion, we manipulate dissimilar quantum sources to produce mutually indistinguishable photons.

T2B.3 • 11:30 am Invited
Optomechanical effects of two-level systems, Juno Suh, Aaron Weinstein, Chan U. Lei, Keith Schwab; *California Inst. of Technology, USA.* Two-level systems are observed to affect quantum measurements with superconducting electromechanical systems via Kerr-like nonlinearity and excess phase noise. We propose a magnetic electromechanical coupling scheme as its solution.

12:00 pm -- 1:30 pm • Lunch, *Meliora Ballroom*

Hoyt Auditorium
1:30 pm -- 2:15 pm
T3 • Session T3
Presider: To be Announced

T3.1 • 1:30 pm Plenary **[Sponsored by OSA - the Optical Society]**
Scalable Photonic Quantum Networks, Ian A. Walmsley, Joshua Nunn, Marco Barbieri, William S. Kolthammer, Xianmin Jin, Animesh Datta, Patrick Michelberger, Tessa Champion, Michael Sprague, Justin Spring, Ben Metcalf, Peter Humphreys; *Univ. of Oxford, UK.* A scalable photonic quantum network will facilitate the preparation of distributed quantum correlations among many light beams, allowing a new regime of state complexity to be accessed, and enabling new quantum-enhanced applications.

2:15 pm - 2:30 pm • Break

Sloan Auditorium

2:30 pm -- 4:00 pm
T4A • Session T4A
Presider: To be Announced

T4A.1 • 2:30 pm Invited
Quantum Coherence in Polariton Fluids, Alberto Amo[1,7], Thomas Boulier[1], Emiliano Cancellieri[1], Romain Hivet[1], Daniele Sanvitto[2,3], Cristiano Ciuti[4], Iacopo Carusotto[5], Romuald Houdre[6], Alberto Bramati[1], Elisabeth Giacobino[1]; [1]*Laboratoire Kastler Brossel, UPMC, ENS, CNRS, France;* [2]*NNL, Istituto Nanoscienze - CNR,, Italy;* [3]*CNB@UniLe, Istituto Italiano di Tecnologia, Italy;* [4]*Laboratoire Matériaux et Phénomènes Quantiques, Université Paris Diderot-Paris 7, CNRS, France;* [5]*BEC-CNR-INFM, Universita di Trento, Italy;* [6]*Institut de Physique de la Matière Condensée, EPFL, Switzerland;* [7]*LPN, CNRS, France.* Exciton-polaritons are composite bosons (exciton-photon mixtures) in semiconductor microcavities. Relying on their strong interactions, we have demonstrated quantum optical effects in the microcavity emission, as well as quantum fluid properties in the polariton propagation.

T4A.2 • 3:00 pm Invited
Direct generation and characterization of continuous-variable multipartite entanglement, Felippe Barbosa[1], Antonio Coelho[1], Katiuscia N. Cassemiro[2], Alessandro S. Villar[2], Marcelo Martinelli[1], Paulo A. Nussenzveig[1]; [1]*Universidade de Sao Paulo, Brazil;* [2]*Universidade Federal de Pernambuco, Brazil.* We demonstrated the direct generation of multipartite continuous-variable entanglement and investigated its robustness against losses. This led to the development of experimental capabilities to fully characterize a six-mode quantum optical state.

T4A.3 • 3:30 pm Invited
Quantum Imaging with light from Four-Wave Mixing, Paul D. Lett[1], Neil Corzo[2], Alberto M. Marino[3], Kevin Jones[4]; [1]*Joint Quantum Inst., National Inst of Standards & Technology, USA;* [2]*ECES Dept., Northwestern Univ., USA;* [3]*Dept. of Physics and Astronomy, Univ. of Oklahoma, USA;* [4]*Dept. of Physics, Williams College, USA.* We have constructed a phase sensitive optical amplifier based on four-wave-mixing in rubidium vapor. This low-gain amplifier operates in the quantum regime and is capable of noiseless amplification of images.

Landers Auditorium

2:30 pm -- 4:00 pm
T4B • Session T4B
Presider: To be Announced

T4B.1 • 2:30 pm Invited
Optical Communication with Invisible Photons, Suhail Zubairy; *Physics and Astronomy, Texas A&M Univ., USA.* It has long been assumed physical particles have to travel between two parties in empty space for exchanging information. However, by using the "chained" quantum Zeno effect, we show, in the ideal asymptotic limit, information can be transferred without any physical carriers.

T4B.2 • 3:00 pm Invited
Control of Work and Cooling in Quantum Thermodynamics, Gershon Kurizki; *Chemical Physics, Weizmann Inst. of Science, Israel.* For quantum systems under manipulations frequent enough to break the Markov approximation, bounds considered fundamental are revisited: the Szilard-Landauer bound on work traded for information, the Carnot engine efficiency bound or Nernst's third law

T4B.3 • 3:30 pm Invited
To be announced, Holger Hofmann; *Hiroshima Univ., Japan.* Not available

4:00 pm -- 4:30 pm • Coffee Break, *Munnerlyn Atrium*

Sloan Auditorium

4:30 pm -- 6:00 pm
T5A • Session T5A
Presider: To be Announced

T5A.1 • 4:30 pm Invited
Noisy Quantum Metrology, Optical Interferometry, and the Time Duration of Physical Processes, Luiz Davidovich, Bruno D. Escher, Márcio Taddei, Nicim Zagury, Ruynet L. Matos; *Universidade Federal do Rio de Janeiro, Brazil.* We develop a general method of parameter estimation for noisy systems, which leads to useful bounds for optical interferometry and the time duration of physical processes, involving generalizations of phase-number and energy-time uncertainty relations.

T5A.2 • 5:00 pm Invited
Restoration of Quantum Entanglement Via Environment-Assisted Error Correction, Ting Yu; *Dept. of Physics, Castle Point on Hudson, USA.* In this talk, I will present an explicit scheme to fully recover a multiple-qubit state subject to a phase damping noise. We establish the theoretical framework and the operational procedure to restore an unknown initial quantum state for an N-qubit model interacting with either individual baths or a common bath. We give an explicit construction of the random unitary (RU) Kraus decomposition for an N-qubit model interacting with a common bath. We also demonstrate how to use only one unitary reversal operation to restore an arbitrary state with phase damping noise. In principle, the initial state can always be recovered with a success probability of 1. Interestingly, we found that non-RU decomposition can also be used to restore some particular entangled states. This may open a new path to restore a quantum state beyond the standard RU scheme.

T5A.3 • 5:30 pm Invited
A Scheme for a Quantum Optical Test of the Minimum Length Scale, Myungshik Kim; *Imperial College London, UK.* The minimum length scale, below which position is not well -defined, has been suggested to modify the uncertainty relation. We propose an experiment which allows one to test such the modication in a novel paramete r regime.

Landers Auditorium

4:30 pm -- 6:00 pm
T5B • Session T5B
Presider: To be Announced

T5B.1 • 4:30 pm Invited
Extracting quantum work statistics by single qubit interferometry, Vlatko Vedral[1,2]; [1]*Physics, Univ. of Oxford, UK;* [2]*National Univ. of Singapore, Singapore.* We propose a scheme to verify the quantum non-equilibrium fluctuation relations. We show that the characteristic function of the work distribution of a quantum system can be extracted from Ramsey interferometry of a probe qubit.

T5B.2 • 5:00 pm Invited
Reliable Entanglement Detection Under Coarse-Grained Measurements, Stephen P. Walborn[1], Lukasz Rudnicki[2], Daniel S. Tasca[3,1], Rafael M. Gomes[4,1], Fabricio Toscano[1]; [1]*Instituto de Física, Universidade Federal do Rio de Janeiro, Brazil;* [2]*Center for Theoretical Physics, Polish Academy of Sciences, Poland;* [3]*School of Physics and Astronomy, Univ. of Glasgow, UK;* [4]*Instituto de Física, Universidade Federal de Goiás, Brazil.* We derive reliable entanglement witnesses for coarse-grained measurements on continuous variable systems. Even for Gaussian states, entropic entanglement witnesses outperform those based on variances. We apply our results to spatial entanglement of photon pairs.

T5B.3 • 5:30 pm Invited
Nonclassicality, entanglement, and nonclassical correlations, Werner Vogel, Jan Sperling; [1]*Univ. of Rostock, Germany.* Nonclassicality of quantum states is characterized by a regularized Glauber-Sudarshan P-function. Related characterizations of entanglement are derived from so-called separability eigenvalue equations. General quantum correlations and the quantification of quantum phenomena are studied.

7:00 pm -- 9:00 pm • Banquet, Awards Ceremony, and Address, *Meliora Ballroom*

Hoyt Auditorium
08:30 am -- 10:00 am
W1 • Session W1
Presider: To be Announced

W1.1 • 8:30 am Invited
3D Computational Ghost Imaging, Baoqing Sun[1], Matthew Edgar[1], Richard Bowman[1], Liberty Vittert[2], Stephen Welsh[1], Adrian Bowman[2], Miles J. Padgett[1]; [1]*School of Physics and Astronomy, Univ. of Glasgow, UK;* [2]*School of Mathematics and Statistics, Univ. of Glasgow, UK.* Computational Ghost Imaging uses projection of random patterns and backscattered signals recorded by a photo-diode to give an image. Extending to multiple detectors gives surface gradients from which the object's 3D form can be reconstructed.

W1.2 • 9:15 am Invited
Coherent Back Scattering and Anderson Localization of Ultra Cold Atoms, Alain Aspect; *Institut d'Optique, France.* Ultra cold atoms in a disordered potential created with a laser speckle are used to study Anderson Localization (AL) and Coherent Back Scattering (CBS). The role of coherence in these examples of quantum transport phenomena is discussed.

10:00 am -- 10:30 am • Coffee Break, *Munnerlyn Atrium*

Sloan Auditorium

10:30 am -- 12:00 pm
W2A • Session W2A
Presider: To be Announced

W2A.1 • 10:30 am Invited
Parametrically generated ultrafast frequency combs : a promising tool for wavelength multiplexed quantum information processing, Claude Fabre, Nicolas Treps, Jonathan Roslund, Renne Medeiros de Araujo, Shifeng Jiang; *Universite Pierre et Marie Curie, France.* We have generated by parametric down-conversion and fully characterized an ultrafast highly multimode frequency comb with genuine quantum entanglement between its different frequency components that has promising applications in wavelength multiplexed quantum information processing

W2A.2 • 11:00 am Invited
Quantum Key Distribution Using Hyperentangled Time-Bin States, Daniel J. Gauthier[1], Christoph F. Wildfeuer[1], Hannah Guilbert[1], Mario Stipcevic[1,2], Bradley G. Christensen[3], Daniel Kumor[3], Paul Kwiat[3], Kevin T. McCusker[4], Thomas Brougham[5], Stephen Barnett[5]; [1]*Dept. of Physics, Duke Univ., USA;* [2]*Rudjer Boskovic Inst., Croatia;* [3]*Dept. of Physics, Univ. of Illinois, USA;* [4]*Dept. of EECS, Northwestern Univ., USA;* [5]*Dept. of Physics, Univ. of Strathclyde, UK.* We describe our progress on achieving quantum key distribution with high photon efficiency and high rate using hyperentanglement. Methods of securing time-bin states and classical error correction appropriate for our high-dimension protocols will be discussed.

Landers Auditorium

10:30 am -- 12:00 pm
W2B • Session W2B
Presider: To be Announced

W2B.1 • 10:30 am Invited
Trapped Atoms in One-Dimensional Photonic Crystals, H. J. Kimble; *California Inst. of Technology, USA.* I describe one-dimensional photonic crystals that support a guided mode suitable for atom trapping within a unit cell, as well as a second probe mode with strong atom-photon interactions. A new hybrid trap is analyzed that combines optical and Casimir-Polder forces to form stable traps for neutral atoms in dielectric nanostructures. By suitable design of the band structure, the atomic spontaneous emission rate into the probe mode can exceed the rate into all other modes by more than tenfold. An unprecedented single-atom reflectivity greater than 90% for the guided probe field should enable diverse investigations of photon-mediated interactions for 1D atom chains and cavity QED.

W2B.2 • 11:00 am Invited
Quantum Coherent Networks, Gerhard Rempe; *Max-Planck-Institut fur Quantenoptik, Germany.* Cavity quantum electrodynamics with single stationary atoms and single flying photons is employed to realize a first quantum-coherent network featuring long-distance quantum-state transfer, controlled atom-atom entanglement and efficient atomic-state teleportation.

Sloan Auditorium	Landers Auditorium

10:30 am -- 12:00 pm
W2A • Session W2A (*cont.*)
Presider: To be Announced

W2A.3 • 11:30 am Invited
To be announced, Carsten Marquart; *Aalborg Universitet, Denmark.* Not available

10:30 am -- 12:00 pm
W2B • Session W2B (*cont.*)
Presider: To be Announced

W2B.3 • 11:30 am Invited
Breakdown of Photon Blockade: A Dissipative Quantum Phase Transition in Zero Dimensions, Howard J. Carmichael; *Univ. of Auckland, New Zealand.* A two-state system coupled to a driven mode of the electromagnetic field undergoes a dissipative quantum phase transition at a critical drive strength. The phase transition marks the breakdown of photon blockade in the Jaynes-Cummings model.

12:00 pm -- 1:30 pm • Lunch Break, *Meliora Ballroom*

Hoyt Auditorium
1:30 pm -- 2:15 pm
W3 • Session W3
Presider: To be Announced

W3.1 • 1:30 pm Invited
Weak Measurement, Uncertainty Relationships, and Experimental Information Tradeoffs, Aephraim M. Steinberg; *Univ. of Toronto, Canada.* Tradeoffs in measurement and information are one of the central themes of quantum mechanics. I will try to summarize in this talk a few of our experiments related to modern views of these topics. In particular, I will try to give an example or two of the power of "weak measurements," both for fundamental physics and for possible precision metrology. One example will involve revisiting the question of Heisenberg's famous principle, and an interpretation which is widespread but has now been experimentally shown to be incorrect. Then I will also discuss ongoing work on a "quantum data compression" protocol which would allow a small-scale quantum memory to store all the extractable information from a larger ensemble of identically prepared systems.

2:15 pm -- 2:30 pm • Break

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Sloan Auditorium	Landers Auditorium

2:30 pm -- 4:00 pm
W4A • Session W4A
Presider: To be Announced

W4A.1 • 2:30 pm Invited
The Time-symmetric Formulation of Quantum Mechanics, Weak Values and the Classical Limit of Quantum Mechanics, Jeff Tollaksen; *Chapman Univ., USA.* The two-state vector formalism provides a complete description of pre- and post-selected quantum systems and has uncovered a host of new quantum phenomena which were previously hidden. The most important feature is that any weak coupling to a pre- and post-selected system is effectively a coupling to a "weak value" which is given by a simple expression depending on the two-state vector. In particular, weak values, are the outcomes of so called "weak measurements" which have recently become a very powerful tool for ultra-sensitive measurements. Using weak values, I will show that the classical limit of quantum mechanics is a far more complicated issue; it is in fact dramatically more involved and it requires a complete revision of all our intuitions. The revised intuitions can then serve as a guide to finding novel quantum effects.

W4A.2 • 3:00 pm Invited
Asking Photons "Where Have They Been?", Lev Vaidman; *Tel Aviv Univ., Israel.* Quantum mechanics does not provide a clear answer to the question: What was the past of a photon which went through an interferometer? Various welcher weg measurements, delayed-choice which-path experiments and weak-measurements of photons in interferometers presented the past of a photon as a trajectory or a set of trajectories. We have carried out experimental weak measurements of the paths of photons going through a nested Mach-Zehnder interferometer which show a different picture: the past of a photon is not a set of continuous trajectories. The photons tell us that they have been in the parts of the interferometer which they could not have possibly reached! Our results lead to rejection of a ``common sense'' approach to the past of a quantum particle. On the other hand, they have a simple explanation within the framework of the two-state vector formalism of quantum theory.

2:30 pm -- 4:00 pm
W4B • Session W4B
Presider: To be Announced

W4B.1 • 2:30 pm Invited
Ultrafast photocurrents induced by polarization-shaped optical pulses: The importance of non-instantaneous coherent effects, Shekhar Priyadarshi, Klaus Pierz, Mark Bieler; *Physikalisch-Technische Bundesanstalt, Germany.* A new type of photocurrent is observed in GaAs nanostructures. The currents only appear if the response of the coherent polarization is non-instantaneous and if the optical excitation pulses have certain polarization shapes.

W4B.2 • 3:00 pm Invited
Controlled Resonances for Sensing and Biology, Martin Plenio; *Inst. of Theoretical Physics, Ulm Univ., Germany.* A single colour center in diamond is used to explain how resonance conditions can be exploited to achieve the dual of goal of sensing minute fields while protecting against environmental noise and how to use these tools to construct a novel room temperature quantum simulator.

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Sloan Auditorium

2:30 pm -- 4:00 pm
W4A • Session W4A *(cont.)*
Presider: To be Announced

W4A.3 • 3:30 pm Invited

Weak Values and Direct Measurement of the Quantum Wavefunction, Robert W. Boyd[1,2]; [1]*Inst. of Optics and Dept. of Physics and Astronomy, Univ. of Rochester, USA;* [2]*Dept. of Physics and School of Electrical Engineering and Computer Science, Univ. of Ottawa, Canada.* We review recent work showing that weak values and weak measurements can be used to perform certain measurements with unprecedented accuracy and moreover can be used to perform a direct measurement of the quantum wavefunction.

Landers Auditorium

2:30 pm -- 4:00 pm
W4B • Session W4B *(cont.)*
Presider: To be Announced

W4B.3 • 3:30 pm Invited

A New Alphabet for Quantum Information, Christopher Fuchs[1]; [1]*Perimeter Inst. for Theoretical Physics, Canada.* Some time ago, Steven Weinberg wrote an article for the New York Review of Books with the title, "Symmetry: A `Key to Nature's Secrets'." So too, I would like to say of quantum information: Only by identifying Hilbert space's most stringent and hard-to-attain symmetries will we be able to unlock quantum information's deepest secrets and greatest potential. In this talk, I introduce the "symmetric informationally complete" (SIC) sets of quantum states as a candidate for that structure. By their aid, one can rewrite quantum states so that they become simply probability distributions, unitary transformations so that they become doubly stochastic matrices, and the Born rule so that it becomes a rather simple variant of the classical law of total probability. These representations hold the potential for entirely new ways of analyzing quantum communication channels and algorithms. Surprisingly however, despite the way they can be used to make quantum theory look formally close to classical information theory, there is also a sense in which the SIC states are as far from classical as possible: For instance, by some measures these states are as sensitive to quantum eavesdropping as any alphabet of quantum states can be. Time permitting, I will show off some of the latest things known about the SICs.

4:00 pm - 4:30 pm • Coffee Break, *Munnerlyn Atrium*

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Sloan Auditorium	Landers Auditorium

4:30 pm -- 6:00 pm
W5A • Session W5A
Presider: To be Announced

W5A.1 • 4:30 pm Invited
Silicon Photonic Platform for Quantum Optics, Michal Lipson; *Cornell Univ., USA.* Not available.

W5A.2 • 5:00 pm Invited
Real-world Bell-state Measurement and Proof-of-Principle Demonstration of Quantum Key Distribution Immune to Detector Attacks, Wolfgang Tittel; *Univ. of Calgary, Canada.* We present the first demonstration of the measurement-device-independent QKD protocol, which removes all side-channels that exploit vulnerabilities in single-photon detectors. Furthermore, the required real-world Bell-state measurement constitutes a previously undemonstrated element of a quantum repeater

W5A.3 • 5:30 pm Invited
Ground state quantum coherences, from quantum beats to strong control, Andres Cimmarusti[1], Burkley Patterson[1], Wanderson Pimenta[2,1], Luis A. Orozco[1], Pablo Barberis-Blostein[3], Howard J. Carmichael[4]; [1]*Physics, Joint Quantum Inst., UMD, USA;* [2]*Physics, Universidade Federal de Minas Gerais, Brazil;* [3]*IIMAS, Unversidad Nacional Autonoma de Mexico, Mexico;* [4]*Physics, Univ. of Auckland, New Zealand.* Second order correlations reveal quantum beats from a coherent ground-state superposition on the undriven mode of a two-mode cavity QED system. Continuous drive induces decoherence due to Rayleigh scattering. We control this with feedback.

4:30 pm -- 6:00 pm
W5B • Session W5B
Presider: To be Announced

W5B.1 • 4:30 pm Invited
Classical Computers Can Not Efficiently Simulate Multi-mode Linear Optical Interferometers with Arbitrary Fock-State Inputs, Jonathan P. Dowling; *Louisiana State Univ., USA.* We explicitly construct the Hilbert space for the interferometer and show that that its dimension scales exponentially with the physical resources required for building and running it.

W5B.2 • 5:00 pm Invited
Hybrid Quantum Information Processing, Akira Furusawa; *Univ. of Tokyo, Japan.* We are working on hybridization of qubit and continuous-variable (CV) technologies to realize universal gate sets for quantum information processing. As a first step, we teleport time-bin qubits with a CV teleporter.

W5B.3 • 5:30 pm Invited
Experimental Boson Sampling, M. Broome[1,2], A. Fedrizzi[1,2], S. Rahimi-Keshari[2], J. Dove[3], S. Aaronson[3], T. Ralph[2], Andrew G. White[1,2]; [1]*Centre for Engineered Quantum Systems, Univ. of Queensland, Australia;* [2]*Centre for Quantum Computer and Communication Technology, Univ. of Queensland, Australia;* [3]*Computer Science and Artificial Intelligence Lab., Massachusetts Inst. of Technology, USA.* Models of intermediate quantum computing are an exciting new avenue for developing devices that can outperform their classical counterparts. BosonSampling—the sampling from a distribution of n photons undergoing some linear-optical process—is a recently developed, and experimentally accessible example of such a task. Here we report our recent experiments, finding BosonSampling to robust, working even with the unavoidable effects of photon loss and non-ideal sources. We discuss its scaling requirements, and what will be required to disprove the Extended Church-Turing thesis, a foundational tenet of modern computer science.

6:30 pm — 7:30 pm • Dinner, *Meliora Ballroom*

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W6.01
A Possible Resolution of the Black Hole Information Paradox, Peter Cameron[1,2]; [1]*brookhaven lab - retired, USA;* [2]*Strongarm Studios, USA.* Nonlocal reduction of entangled states is clarified by considering the role of background independent scale-invariant quantum impedances in decay/decoherence of unstable elementary particles, providing simple resolution of the black hole information paradox.

W6.02
A long-lived solid-state quantum memory at the single photon level, Nuala Timoney, Imam Usmani, Pierre Jobez, Mikael Afzelius, Nicolas Gisin; *Group of Applied Physics, Univerisity of Geneva, Switzerland.* We show storage of a few photon optical pulse as a spin-wave in a crystal, preserving the states' coherence. We show how it is possible to extend the storage time and increase the process efficiency.

W6.03
Biphoton Generation with an Optimized Wavefront for Free-Space Propagation by means of Adaptive Optics, Mattia Minozzi[1], Stefano Bonora[3], Alexander V. Sergienko[2], Giuseppe Vallone[1], Paolo Villoresi[1]; [1]*Università di Padova, Italy;* [2]*Boston Univ., USA;* [3]*Inst. for Photonics and Nanotechnology, Nat. Res. Council, Italy.* The pump wavefront which generates photon pairs by spontaneous parametric down conversion is optimized using a feedback which optimize the coincidence count after propagation along a suitable path. The active element is a deformable mirror.

W6.04
Can Quantum Memories operate at Room Temperature?, Eden Figueroa[1,2], Andreas Neuzner[2], Tobias Latka[2], Josef Schupp[2], Christian Noelleke[2], Andreas Reiserer[2], Stephan Ritter[2], Gerhard Rempe[2]; [1]*Physics and Astronomy, Stony Brook Univ., USA;* [2]*Max Planck Inst. of Quantum Optics, Germany.* We use a vapor of 87Rb atoms and store light pulses containing on average a single photon using EIT. The retrieved excitations outnumber concurrent background photons by a factor of 3.

W6.05
Coherently generated of vortex superpositions in Bose-Einstein Condensates and their applications, Kishor T. Kapale[1], Jonathan P. Dowling[2]; [1]*Dept. of Physics, Western Illinois Univ., USA;* [2]*Dept. of Physics and Astronomy, Louisiana State Univ., USA.* We present methods for optical excitation of coherent superpositions of vortices in Bose-Einstein Condensates through coupling with orbital angular momentum of light. We discussion applications to quantum information, gyroscopy and generation of Schrödinger Cat states.

W6.06
Determining the Lower Limit of Human Vision Using a Single-Photon Source, Rebecca Holmes[1], Bradley G. Christensen[1], Whitney Street[2], Cory Alford[1], Ranxiao F. Wang[2], Paul G. Kwiat[1]; [1]*Physics, Univ. of Illinois, USA;* [2]*Psychology, Univ. of Illinois, USA.* We discuss the use of a source of single photons to investigate possible single-photon vision in humans.

W6.07
Direct Verification of Yang-Baxter Equation, CHAO ZHENG[1,2], Gui Lu Long[1,2]; [1]*Dept. of Physics, Tsinghua Univ., China;* [2]*State Key Lab. of Low-Dimensional Quantum Physics, Tsinghua Univ., China.* Yang-Baxter equation has become an important tool in a variety of fields of physics. In this work, we report the first direct experimental simulation of the Yang-Baxter equation using linear quantum optics.

W6.08
Efficient tools for quantum metrology with decoherence, Jan Kolodynski, Rafal Demkowicz-Dobrzanski; *Faculty of Physics, Univ. of Warsaw, Poland.* We propose methods of quantifying precision gain in quantum metrological schemes that correctly incorporate decoherence effects, predicting the enhancement to scale super-classically only for moderate -sized probes and limiting the maximal gain to a constant factor.

W6.09
Entangled Mechanical Cat States via Single Photon Conditional Optomechanics, Uzma Akram, Warwick P. Bowen, Gerard J. Milburn; *Univ. of Queensland, Australia.* We condition single photon driving of an interferometer with two optomechanical systems on no detections. Conditioning on long detection times of the photon from the composite system results in an entangled mechanical cat state.

W6.10
Experimental Test of Error-Disturbance Uncertainty Relations by Weak Measurements, Fumihiro Kaneda[1], So-Young Baek[1], Masanao Ozawa[2], Keiichi Edamatsu[1]; [1]*Tohoku Univ., Japan;* [2]*Nagoya Univ., Japan.* We experimentally test the error-disturbance relations for generalized measure- ment of photon-polarization by weak measurements. Our results exemplify the violation of Heisenberg's uncertainty relation, yet validates Ozawa's relation.

May Room
7:30 pm -- 10:00 pm
W6 • QIM Poster Session *(cont.)*

W6.11

Experimental super resolved phase measurements at the shot noise limit, Lior Cohen, Liat Dovrat, Daniel Istrati, Hagai S. Eisenberg; *Racah Institue of Physics, Hebrew Univ. of Jerusalem, Israel.* Using photon-number resolving detectors, we directly measure the parity of coherent states in a Mach-Zehnder interferometer. Phases are super resolved by a factor of 150 and shot noise limited measurements are demonstrated with 200 photons.

W6.12

Experimental test of error-disturbance relations in generalized photon-polarization measurements, So-Young Baek[1], Fumihiro Kaneda[1], Masanao Ozawa[2], Keiichi Edamatsu[1]; *[1]Research Inst. of Electrical Communication, Tohoku Univ., Japan; [2]Graduate School of Information Science, Nagoya Univ., Japan.* We report an experimental test of Ozawa's relation for a single-photon polarization qubit, exploiting an indirect measurement model that breaks Heisenberg's relation throughout the range of our experimental parameter and yet validates Ozawa's relation.

W6.13

Generation of Orbital Angular Momentum Bell States and their Verification via Accessible Nonlinear Witnesses, Megan Agnew[1,2], Jeff Salvail[1,3], Jonathan Leach[1,4], Robert W. Boyd[1,5]; *[1]Physics, Univ. of Ottawa, Canada; [2]Physics, Univ. of Waterloo, Canada; [3]Physics, Simon Fraser Univ., Canada; [4]Physics, Heriot-Watt Univ., UK; [5]Physics, Univ. of Rochester, USA.* We produce all four Bell states in the orbital angular momentum degree of freedom and use a new class of accessible nonlinear entanglement witnesses to verify their entanglement.

W6.14

Increasing the Signal-to-Noise Ratio in Weak-Value Measurements, Courtney Byard[1], Trent Graham[1], Ariel Danan[3], Andrew Jordan[2], Paul G. Kwiat[1]; *[1]Physics, Univ. of Illinois, USA; [2]Physics and Astronomy, Univ. of Rochester, USA; [3]Raymond and Beverly Sackler School of Physics and Astronomy, Tel-Aviv Univ., Israel.* By recycling non-post selected photons through a Sagnac interferometer in our optical weak measurement of a mirror tilt, we double the detected intensity, resulting in a signal-to-noise ratio improvement of 1.57 over un-recycled experiments.

W6.15

Information Reconciliation in Higher Dimensional Quantum Cryptography, Bradley G. Christensen[1], Daniel Kumor[1], Kevin T. McCusker[1,2], Venkat Chandar[3], Daniel J. Gauthier[4], Paul G. Kwiat[1]; *[1]Dept. of Physics, Univ. of Illinois at Urbana-Champaign, USA; [2]Dept. of Physics & Astronomy, Northwestern Univ., USA; [3]Dept. of Electrical Engineering and Computer Science, Massachusetts Inst. of Technology, USA; [4]Dept. of Physics, Duke Univ., USA.* We report on a high-speed quantum cryptography system that utilizes simultaneous entanglement in polarization and time-bins. We also show a practical implementation of information reconciliation using concatenated low density parity check codes.

W6.16

Manipulation of Quantum Correlations and Squeezing Enhancement in a Cascaded Four-Wave Mixing System, Jietai Jing, Jia Kong, Hailong Wang, Cunjin Liu, Zhongzhong Qin, Weiping Zhang; *East China Normal Univ., China.* We experimentally demonstrate that quantum correlations from a cascaded four wave mixing process can be manipulated by controlling the relative phase inside this system. It results in a squeezing enhancement of about 4dB.

W6.17

Matrix product states for quantum metrology, Marcin Jarzyna, Rafal Demkowicz-Dobrzanski; *Faculty of Physics, Univ. of Warsaw, Poland.* We demonstrate that the optimal states in lossy quantum interferometry may be efficiently simulated with low rank matrix product states which is related to the nature of the precision scaling in presence of decoherence.

W6.18

Multi-Spatial-Mode Optical Memory with Collective Raman Scattering Interface, Radoslaw Chrapkiewicz[1], Wojciech Wasilewski[1]; *[1]Faculty of Physics, Univ. of Warsaw, Poland.* We show that quantum memories can be implemented in atomic ensembles in a multi-spatial-mode regime using collective Raman scattering. It can be accomplished by optimization of diffusional decoherence which we measure by a novel method.

W6.19

Orbital Angular Momentum Joint Spectrum Analysis for Efficient Object Recognition, Andrew Fraine[1], Nestor Uribe-Patarroyo[1], David Simon[1,2], Olga Minaeva[3], Alexander V. Sergienko[1,4]; *[1]Dept. of Electrical and Computer Engineering, Boston Univ., USA; [2]Dept. of Physics and Astronomy, Stonehill College, USA; [3]Dept. of Biomedical Engineering, Boston Univ., USA; [4]Dept. of Physics, Boston Univ., USA.* Object recognition exploiting the two-dimensional orbital angular momentum joint spectrum using pairs of correlated photons is presented. The detection of rotational symmetries demonstrates a sparse sensing technique relevant to remote sensing and biological applications.

W6.20

Photonic Three-Qubit CNOT Gates Using Spatial Light Modulators, Kumel Kagalwala[1], Giovanni Di Giuseppe[1,2], Ayman Abouraddy[1], Bahaa Saleh[1]; [1]*CREOL, College of Optics and Photonics, Univ. of Central Florida, USA;* [2]*Physics Division, School of Science and Technology, Univ. of Camerino, Italy.* We experimentally demonstrate linear and deterministic, single-photon three-qubit controlled-NOT (CNOT) gates implemented by a polarization-sensitive spatial light modulator. The polarization qubit acts as the control, whereas the photon spatial-parity along x and y directions are the target qubits.

W6.21

Polarization Independent Photon Storage with Variable Time Delay, Jia Jun Wong[1], Bradley G. Christensen[1], Paul G. Kwiat[1], Michael Goggin[3], Katherine Crimmins[1], Kevin T. McCusker[2]; [1]*Physics, Univ. of Illinois at Urbana Champaign, USA;* [2]*Physics & Astronomy, Northwestern Univ., USA;* [3]*Physics, Truman State Univ., USA.* We discuss a high-efficiency photon storage system that is independent of photon's polarization. This scheme may be critical for enhancing the efficiency of existing quantum computers and quantum storage devices for qubits.

W6.22

Polarization encrypted quantum teleportation using two type-II Parametric Down Converters, Daniel B. Erenso, Daniel Bonior, Benjamin Bunnell, Hannah Norris; *Middle Tennessee State Univ., USA.* A Physical scheme for quantum teleportation that uses photons emitted by two type-II spontaneous parametric down converters (SPDC) is proposed and studied. We have analyzed the fidelity in comparison with photons emitted by single SPDC.

W6.23

Polarization-dependent Focusing, David Schmid[1], Ting-Yu Huang[1,2], Radhika Dirks[1,3], Onur Hosten[1,4], Paul G. Kwiat[1]; [1]*UIUC, USA;* [2]*National Chiao Tung Univ., Taiwan;* [3]*Shell Technology Ventures, USA;* [4]*Stanford Univ., USA.* We present two methods of creating two orthogonally-polarized focal points at customizable relative locations. These schemes may be critical for enhancing entanglement sources and other applications.

W6.24

Practical Measurement Device Independent Quantum Key Distribution, Feihu Xu[1], Marcos Curty[2], Bing Qi[1,3], Wei Cui[3], Charles Ci Wen Lim[5], Kiyoshi Tamaki[4], Hoi-Kwong Lo[1,3]; [1]*Electrical and Computer Engineering, Univ. of Toronto, Canada;* [2]*Signal Theory and Communications, Univ. of Vigo, Spain;* [3]*Physics, Univ. of Toronto, Canada;* [4]*NTT Basic Research Laboratories, NTT Corporation, Japan;* [5]*Group of Applied Physics, Univ. of Geneva, Switzerland.* We analyze real-life implementations of measurement-device-independent quantum-key-distribution (MDI-QKD): a general system model, a finite-decoy protocol and a finite-key analysis. Our work is relevant to not only QKD but also general experiments on quantum interference.

W6.25

Pre-management of Entanglement Sudden Death, Xiao-Feng Qian; *Univ. of Rochester, USA.* We report a summary of our work on management of entanglement sudden death (ESD) through initial conditions. ESD phases are shown for a generic two-qubit system that undergoes local but unbalanced amplitude damping dissipations.

W6.26

Quantum Algorithm to Calculate Electromagnetic Scattering Cross Sections, Brian D. Clader, Bryan Jacobs, Chad Sprouse; *Johns Hopkins Applied Physics Lab, USA.* We present a quantum algorithm that can solve a linear system exponentially faster than the best classical algorithm. We show how one can use it to compute the electromagnetic scattering cross-section of an arbitrary target.

W6.27

Quantum Correlation of Telecom Wavelength Photon-pair through Multiple Scattering Media, Yong Meng Sua[1], John Malowicki[2], Kim Fook Lee[1]; [1]*Dept. of Physics, Michigan Technological Univ., USA;* [2]*Air Force Research Lab, USA.* We investigate the effect of multiple scattering on the telecom wavelength photon-pair. Our findings show that quantum correlation of polarization-entangled photon-pair is better preserved than polarization-correlated photon-pair in multiple scattering processes.

W6.28

Quantum Discord with Varied Bloch Vectors, Shiqun Zhu[1], Jingying Yao[1], Yuli Dong[1]; [1]*School of Physical Science and Technology, Soochow Univ., China.* When Bloch vectors are perpendicularly oriented, the level surfaces of quantum discord are formed by three interaction "tubes" along orthogonal directions. They shrink or expand when the Bloch vectors or quantum discord are increased.

W6.29
Quantum Non-Demolition Measurement through Cavity QED in the Strong-Coupling Regime, Jian Yang, Paul G. Kwiat; *Physics, Univ. of Illinois at Urbana-Champaign, USA.* We theoretically study photon-photon interactions mediated by a cavity-atom system in the strong-coupling regime of cavity quantum electrodynamics (QED), which may be harnessed for quantum non-demolition (QND) measurements.

W6.30
Quantum Operator Permutation by Optical Means, Timothy Rambo[1], Joseph B. Altepeter[1], Giacomo M. D'Ariano[2,3], Prem Kumar[1]; *[1]EECS, Northwestern Univ., USA; [2]Dipartimento di Fisica, Università di Pavia, Italy; [3]Istituto Nazionale di Fisica della Materia, Università di Pavia, Italy.* Quantum functions have been proposed as a potentially more intuitive design methodology for quantum computations. We present a proposed experimental architecture for implementing a proof-of-principle functional algorithm using photonic qubits and quantum switching technology.

W6.31
Quantum Sensitivity, Bruno Escher; *Instituto de Física, Universidade Federal do Rio de Janeiro, Brazil.* We show that the minimal uncertainty in single-parameter estimation is given by the ratio between noise and sensibility of a well-calibrated observable. Therefore, the problem of reaching the ultimate precision limit is reduced to a calibration issue.

W6.32
Quantum Speed Limit for Physical Processes, Márcio Taddei, Bruno Escher, Luiz Davidovich, Ruynet L. Matos; *Physics Inst., Federal Univ. of Rio de Janeiro, Brazil.* We present an attainable upper bound on the quantum speed limit of general physical processes based on the quantum Fisher information. This result allows one to tackle experimentally more realistic open-system dynamics.

W6.33
Quantum correlations in a mixed full rank qubit-qudit system: Discord and entanglement in the Jaynes-Cummings model, Juan Nicolas Quesada; *Univ. of Toronto, Canada.* The quantum correlations of qubit-qudit states that satisfy the constraint of having coherences only between elements of the computational basis with the same number excitations and that occur naturally in the Jaynes-Cummings model are studied.

W6.34
Withdrawn

W6.35
Quantum tomography of inductively created multiphoton states, Eli Megidish, Assaf Halevy, Tomer Shacham, Tom Dvir, Hagai S. Eisenberg; *Physics, Racah Inst. of Physics, Hebrew Univ. of Jerusalem, Israel.* Using the measured density matrix of a four photon GHZ state, created in our unique inductive setup, we calculated the density matrices of possible states with higher photon numbers and their entanglement and non-locality violation

W6.36
Room-Temperature Single Photon Source: Nanocrystals in Photonic Bandgap Microcavities, Justin Winkler[1], Svetlana G. Lukishova[2], Luke Bissell[3], David Goldberg[4], Vinod M. Menon[4]; *[1]Physics, Univ. of Rochester, USA; [2]The Inst. of Optics, Univ. of Rochester, USA; [3]Air Force Research Lab., Wright-Patterson Air Force Base, USA; [4]Physics, Queens College-CUNY, USA.* Single-photon sources based on nanocrystals in 1-D photonic bandgap microcavities (cholesteric liquid crystal and Bragg reflectors) are reported. Studied emitters include nanocrystal quantum dots, color centers in nanodiamonds, and trivalent rare-earth ions in nanocrystals.

W6.37
Self Correcting Quantum Random Number Generators using Tapered Amplifiers, Raphael C. Pooser, Phil Evans, Travis Humble, Warren Grice, Brian Williams; *Oak Ridge National Lab., USA.* We present a new implementation of a quantum random number generator that consists of tapered amplifier optical semiconductor devices and an array of random number registration techniques, including quantum feedback/forward control for removing bias.

W6.38
Self-calibrating tomography for non-unitary processes, Juan Nicolas Quesada, Daniel F. James, Agata M. Branczyk; *Univ. of Toronto, Canada.* We extend the idea of using an incompletely characterized process to do quantum state tomography by including the possibility that the process is not unitary. We exemplify this by doing tomography of a two-level atom.

W6.39

Single-Photon Absorption and Reemission in Two-Level Cold Atoms, Shanchao Zhang[1], Chang Liu[1], Shuyu Zhou[1], Chih-Sung Chuu[2], Michael M. T. Loy[1], Shengwang Du[1]; *[1]Physics, Hong Kong Univ. of Science and Technology, Hong Kong; [2]Physics, National Tsing Hua Univ., Taiwan.* With narrow-band heralded single photons, we demonstrate that the single-photon absorption and reemission processes in a two-level atomic ensemble can be coherently controlled by shaping the incident photon temporal waveform.

W6.40

Single-Photon Differential-Phase-Shift Quantum Key Distribution, Chang Liu[1], Shanchao Zhang[1], Luwei Zhao[1], Peng Chen[1], C. -H. Fred Fung[2], Hoi Fung Chau[2], Michael M. T. Loy[1], Shengwang Du[1]; *[1]Physics, The Hong Kong Univ. of Science and Technology, Hong Kong; [2]Physics, Univ. of Hong Kong, Hong Kong.* We demonstrate differential-phase-shift quantum key distribution using narrowband heralded single photons with amplitude-phase modulations. We obtain a quantum bit error rate as low as 3.06% which meets the unconditional security requirement.

W6.41

Single-Photon Level Induced Nonlinear Effects in Parametric Self-Oscillation Regime, Zhifan Zhou[1], Jietai Jing[1], Zhongzhong Qin[1], Yami Fang[1], Ryan Glasser[2], Ulrich Vogl[2], Weiping Zhang[1]; *[1]East China Normal Univ., China; [2]National Inst. of Standards and Technology, USA.* We prepare a parametric self-oscillation regime in hot rubidium vapor and observe single-photon level induced ultraslow matched pulses by four-wave mixing. The delay times are dependent on the few-photon input states.

W6.42

Single-Photon Scattering in One-Dimensional Coupled-Resonator Waveguide Nonlocally Coupled to a Nanocavity, Shiqun Zhu, Zheyong Zhang, Yuli Dong; *Soochow Univ., China.* The scattering properties of a single photon in a dissipative environment is investigated when the photon is transporting in a coupled-resonator waveguide nonlocally coupled to a nanocavity with a three-level atom embedded in it.

W6.43

Stochastic Path Integral for Pre-/Post-selected Continuous Quantum Measurement, Areeya Chantasri, Justin Dressel, Andrew Jordan; *Dept. of Physics and Astronomy, Univ. of Rochester, USA.* We propose a stochastic-path-integral method to study a continuously measured qubit. Results for the most-likely qubit trajectories in Hilbert space contrained by pre- and post-selection as boundary conditions are presented.

W6.44

Super-Dense Teleportation using Hyperentangled Photons, Trent M. Graham[1], Julio T. Barreiro[2], Herbert J. Bernstein[3], Paul G. Kwiat[1]; *[1]Physics, Univ. of Illinois at Urbana-Champaign, USA; [2]Ludwig-Maximilians-Universitat, Germany; [3]Hampshire College, USA.* We use photons simultaneously entangled in polarization and orbital angular momentum to implement super-dense teleportation, a novel remote state preparation technique that communicates quantum information between remote parties with reduced classical resources.

W6.45

Super-resolution imaging using spin-dependent fluorescence in bulk diamond, Edward H. Chen[1], Igal Bayn[1], Matthew E. Trusheim[1], Ophir Gaathon[1], Tim Schröder[1], Luozhou Li[2], Xinwen Yao[2], Dirk R. Englund[1]; *[1]Electrical Engineering and Computer Science, and Research Lab of Electronics, Massachusetts Inst. of Technology, USA; [2]Electrical Engineering, Columbia Univ., USA.* By modulating the fluorescence brightness of nitrogen-vacancy (NV) defect centers in bulk diamond, we demonstrate a `deterministic emitter switch microscopy' (DESM) technique that enables super-resolution imaging with localization down to several tens of nanometers.

W6.46

Superdense Coding for Dual-Quantum Channel Quantum Key Distribution, Nilambari Gawand, Mayssaa El Rifai, Gregory MacDonald, Pramode K. Verma; *Telecommunications Engineering, The Univ. of Oklahoma, USA.* We propose an enhancement to the BB84 protocol that uses superdense coding over dual-quantum channel. The enhanced protocol offers higher key efficiency, real-time detection of the man-in-the-middle attack, and high resistance to the photon number splitting attack.

W6.47

Symmetry Breaking and Topological Defect Formation in Ion Coulomb Crystals, Jonas Keller[1], Karsten Pyka[1], Heather L. Partner[1], Ramil Nigmatullin[2,3], Tobias Burgermeister[1], David M. Meier[1], Kristijan Kuhlmann[1], Alex Retzker[4], Martin Plenio[2,3], Wojciech H. Zurek[5], Adolfo del Campo[5,6], Tanja E. Mehlstaeubler[1]; *[1]QUEST Inst., Physikalisch-Technische Bundesanstalt, Germany; [2]Inst. for Theoretical Physics, Ulm Universtiy, Germany; [3]Dept. of Physics, Imperial College, UK; [4]Racah Inst. of Physics, The Hebrew Univ. of Jerusalem, Israel; [5]Theoretical Division, Los Alamos National Lab., USA; [6]Center for Nonlinear Studies, Los Alamos National Lab., USA.* Symmetry breaking phase transitions play an important role in nature. We create topological defects in ion Coulomb crystals and measure the scaling of kink creation to test the Kibble-Zurek mechanism.

W6.48

Ultrafast Coherent Measurement of Time-Bin Qubits Using Chirped-Pulse Upconversion, John M. Donohue[1,2], Megan Agnew[1,2], Jonathan Lavoie[1,2], Kevin J. Resch[1,2]; [1]*Inst. for Quantum Computing, Canada;* [2]*Physics and Astronomy, Univeristy of Waterloo, Canada.* Using shaped pulses and nonlinear optics, we have experimentally demonstrated projective measurement of time-bin encoded photons with temporal separations two orders of magnitude smaller than detector resolution by converting timing information to frequency.

W6.49

Using hyperentanglement to study multipartite entanglement, Aditya N. Sharma[1], Kevin T. McCusker[2], Julio T. Barreiro[3], Paul G. Kwiat[1]; [1]*Univ. of Illinois, USA;* [2]*Northwestern Univ., USA;* [3]*Ludwig Maximilians Universitat fur Physik, Germany.* We present an experiment in which hyperentangled photon pairs are used to prepare and study multipartite entangled states, including the bound-entangled Smolin state.

W6.50

Weak Values are Universal in von Neumann Measurements, Justin Dressel, Andrew Jordan; *Physics and Astronomy, Univ. of Rochester, USA.* We refute the widely held belief that the quantum weak value necessarily pertains to weak measurements. We show that a von Neumann coupled detector is always described by generalized joint weak values.

W6.51

X-matrices as a platform for studying multipartite entanglement, Seyed Mohammad Hashemi Rafsanjani, Shantanu Agarwal, Curtis J. Broadbent, Joseph H. Eberly; *Univ. of Rochester, USA.* We derive an algebraic formula for the genuinely multipartite entanglement of a N-qubit X state. The entanglement dynamics of a N-qubit GHZ-state is a decoherence scenario. We also show that the mixedness of a state limits its entanglement, and the critical mixedness, beyond which no X-state is entangled, increases with the number of qubits.

W6.52

Observation of the Emergence of Multipartite Entanglement Between a Bipartite System and Its Environment, Osvaldo Jiménez Farías, Gabriel Aguilar, Andrea Valdés Hernandez, Paulo Henrique Souto Ribeiro, Luiz Davidovich, Stephen Patrick Walborn; *Instituto de Física, Universidade Federal de Rio de Janeiro, Rio de Janeiro, Brazil.* The dynamics of the environment is usually experimentally inaccessible and thus ignored for open systems dynamics. We overcome this difficulty by using an interferometer that allows the full access to all environmental degrees of freedom.

W6.53

Ultra-low Noise Upconversion Single-Photon Detector in the Telecom Band, Guoliang Shentu[1], Jason S. Pelc[2], Xiao-Dong Wang[3], Martin M. Fejer[2], Qiang Zhang[1], Jian-Wei Pan[1]; [1] *Shanghai Branch, Hefei National Lab. for Physical Sciences at Microscale and Dept. of Modern Physics, Univ. of Science and Technology of China, ShangHai, ShangHai, China;* [2]*College of Physics and Electronic Engineering, Stanford Univ., Stanford, CA, USA;* [3]*College of Physics and Electronic Engineering, Northwest Normal Univ., Lanzhou, GanSu, China.* We demonstrate upconversion single-photon detection for the 1550-nm band using a PPLN waveguide, long-wavelength pump, and narrowband filtering. We achieve total-system detection efficiency of 30% with noise at the dark-count level of a silicon APD.

W6.54

Experimental Realization of Measurement Device Independent Quantum Key Distribution, Yang Liu[1], Teng-Yun Chen[1], Liu-Jun Wang[1], Hao Liang[1], Guoliang Shentu[1], Jian Wang[1], Ke Cui[1], Hua-Lei Yin[1], Nai-Le Liu[1], Li Li[1], Xiong-Feng Ma[2], Jason S. Pelc[3], Martin M. Fejer[3], Cheng-Zhi Peng[1], Qiang Zhang[1], Jian-Wei Pan[1], [1] *Shanghai Branch, Hefei National Lab. for Physical Sciences at Microscale and Dept. of Modern Physics, USTC, Hefei, China;* [2] *Center for Quantum Information, Inst. for Interdisciplinary Information Sciences, Tsinghua Univ., Beijing, China;* [3] *E. L. Ginzton Lab.,, Stanford Univ., Stanford, CA, USA.* We report a complete experimental realization of measurement device independent quantum key distribution system with decoy method, which closes loopholes in both source and detection. 25-kbit secure key is generated over a 50-km fiber link.

W6.55

Measurement Back-action in a Two-component Bose-Einstein Condensate, Ebubechukwu Ilo-Okeke[1,2], Tim Byrnes[1], [1]*National Inst. of Informatics, Chiyoda-ku, Tokyo, Japan;* [2]*Dept. of Physics, Federal Univ. of Technology, Owerri, Imo State, Nigeria.* We investigate a non-destructive homodyne measurement of atomic condensates. We derive expression for the measurement operator on the atomic states due to the photon measurement, and characterize the back-action of the measurement on atomic states.

Hoyt Auditorium
8:30 am -- 10:00 am
Th1 • Session Th1
Presider: To be Announced

Th1.1 • 8:30 am Invited
Quantum Information Processing with Trapped Ions, Rainer Blatt[1,2]; [1]*Inst. for Experimental Physics, Univ. of Innsbruck, Austria;* [2]*Inst. for Quantum Optics and Quantum Information, Austrian Academy of Sciences, Austria.* Entangling operations and quantum simulations are performed using an extended toolbox for a trapped-ion quantum computer. Decoherence of large entangled states is measured and open-system simulations are carried out, scalability is investigated with a CQED setup.

Th1.2 • 9:15 am Invited
Nonlinear Optics at the Few-Photon Level, Alex Gaeta; *School of Applied and Engineering Physics, Cornell Univ., USA.* Through use of Rb-filled photonic crystal fibers, we demonstrate intensity modulation and cross-phase modulation at the few photon level in a single pass without the use of a cavity. Such a system can be applied to quantum information applications.

10:00 am -- 10:30 am • Coffee Break, *Munnerlyn Atrium*

Sloan Auditorium

10:30 am -- 12:00 pm
Th2A • Session Th2A
Presider: To be Announced

Th2A.1 • 10:30 am Invited
A tunable AC atom interferometer magnetometer, Danielle Braje[1], Charles Adler[2], Jon P. Davis[3], Francesco A. Narducci[3]; [1]*RF and Quantum Systems Tech. Group, MIT Lincoln Lab., USA;* [2]*Dept. of Physics, St. Mary's College of Maryland, USA;* [3]*EO Sensors Division, Naval Air Systems Command, USA.* We demonstrate an atom interferometer designed to measure magnetic fields and field gradients. Here, we study various pulse sequences and show how they can be manipulated to filter unwanted frequencies and to enhance desired frequencies

Th2A.2 • 11:00 am Invited
Quantum Networks with Atoms, Phonons, and Photons, Chris Monroe; *Physics, Joint Quantum Inst. and Univ. of Maryland, USA.* Trapped atomic ions are the most advanced experimental platform for many-body entanglement and quantum information processing. Recent results in local entanglement between trapped ions for uses in quantum simulation of nontrivial spin models will be discussed, as well as the use of probabilistic photonic connections for the generation of larger quantum networks and the propagation of entanglement over large distance.

Th2A.3 • 11:30 am Invited
Interaction Between Light and Matter: A Photon Wave Function Approach, Carlos Monken, Pablo L. Saldanha; *Physics, UFMG, Brazil.* The Bialynicki-Birula-Sipe photon wave function formalism is extended to include the interaction between photons and continuous lossless media. This extended formalism leads to a new method for describing quantum interactions between light and matter.

Landers Auditorium

10:30 am -- 12:00 pm
Th2B • Session Th2B
Presider: To be Announced

Th2B.1 • 10:30 am Invited
Micro-Macro Entanglement, Christoph Simon; *Univ. of Calgary, Canada.* Does quantum physics apply on all scales? I describe recent theoretical and experimental work on the creation and detection of micro-macro entanglement involving single photons and intense light beams.

Th2B.2 • 11:00 am Invited
Directional Superradiant Emission from Independent Classical Sources, Steffen Oppel[1,2], Ralph Wiegner[1], Girish S. Agarwal[2,3], Joachim von Zanthier[1,2]; [1]*Physics, Univ. of Erlangen-Nurember, Germany;* [2]*Erlangen Graduate School in Advanced Optical Technologies (SAOT), Univ. of Erlangen-Nurember, Germany;* [3]*Physics, Oklahoma State Univ., USA.* We show that directional superradiant emission can be observed not only from two-level atoms interacting with a common radiation field but also from statistically independent classical light sources. Experimental results confirm the theoretical predictions.

Th2B.3 • 11:30 am Invited
Single Photon Nonlinearities and Macroscopic Entanglement, Rob Thew; *Universite de Geneve, Switzerland.* I will discuss two recent experiments at opposite extremes of quantum photonics: the demonstration of an integrated nonlinear optics scheme capable of photon-photon interactions, and the generation and characterisation of macroscopic photonic entanglement.

12:00 pm -- 1:30 pm • Lunch Break, *Meliora Ballroom*

Hoyt Auditorium
1:30 pm -- 2:15 pm
Th3 • Session Th3
Presider: To be Announced

Th3.1 • 1:30 pm Invited

The End of Local Realism, Paul G. Kwiat[1], Bradley G. Christensen[1], Kevin T. McCusker[1,5], Joseph B. Altepeter[1,6], Brice Calkins[2], Thomas Gerrits[2], Adriana Lita[2], Aaron Miller[3,2], Lynden Shalm[2], SaeWoo Nam[2], Nicolas Brunner[4]; [1]*Physics, Univ of Illinois at Urbana-Champaign, USA;* [2]*National Inst. of Standards and Technology, USA;* [3]*Physics, Albion College, USA;* [4]*Physics, Univ of Geneva, Switzerland;* [5]*EECS, Northwestern Univ., USA;* [6]*Berberian & Co., USA.* Using a high-quality source of non-maximal polarization entanglement, optimized filters and collection optics, and ultra-high efficiency photon counters, we

2:15 pm - 2:30 pm • Break

Sloan Auditorium

2:30 pm -- 4:00 pm
Th4A • Session Th4A
Presider: To be Announced

Th4A.1 • 2:30 pm Invited

Null Values and Quantum State Discrimination, Alessandro Romito[1]; [1]*Freie Universität Berlin, Fachbereich Physik, Germany.* Not available.

Th4A.2 • 3:00 pm Invited

Experimental Demonstration of All-Optical Switching Using the Quantum Zeno Effect, Kevin T. McCusker, Yu-Ping Huang, Abijith S. Kowligy, Prem Kumar; *Electrical Engineering and Computer Science, Northwestern Univ., USA.* We experimentally demonstrate interaction-free all-optical switching via the quantum Zeno effect. The switch contrast is 35:1, and the experimental data matches a parameter-free fit. We discuss possible applications and future extensions.

Landers Auditorium

2:30 pm -- 4:00 pm
Th4B • Session Th4B
Presider: To be Announced

Th4B.1 • 2:30 pm Invited

Schmidt-mode and Stokes-vector representations of biphoton polarization qutrits, Mikhail Fedorov; *General Physics Instutute, Russian Federation.* Schmidt modes of biphoton polarization qutrits are found in a general form. Representation in terms of Schmidt-mode Stokes vectors at the Poincaré sphere is suggested. Schemes of experiments for measurements and practical applications are discussed.

Th4B.2 • 3:00 pm Invited

High-capacity Fibonacci Key Coding in Quantum Communication, Alexander V. Sergienko[1,4], David Simon[2], Nate Lawrence[1], Jacob Trevino[3], Luca Dal Negro[1]; [1]*Dept. of ECE, Boston Univ., USA;* [2]*Dept. of Physics and Astronomy, Stonehill College, USA;* [3]*Div. of Materials Science & Engineering, Boston Univ., USA;* [4]*Dept. of Physics, Boston Univ., USA.* We propose a new physical mechanism for high capacity quantum key distribution. The protocol is implemented by randomly encoding the Fibonacci sequence onto entangled OAM states, allowing secure generation of long keys from few photons.

Sloan Auditorium	Landers Auditorium

2:30 pm -- 4:00 pm
Th4A • Session Th4A *(cont.)*
Presider: To be Announced

Th4A.3 • 3:30 pm Invited
Quantum state steering by real-time adaptive measurements on a single nuclear spin, Machiel Blok[1], Cristian Bonato[1], Slava Dobrovitski[2], Ronald Hanson[1]; [1]*Delft Univ. of Technology, Netherlands;* [2]*2 Ames Lab. and Iowa State Univ., USA.* We present our most recent results on partial measurements of a nuclear spin in which the inevitable measurement back-action is controllably reduced. The post-selected measurement results can give rise to weak values. By using a real-time adaptive scheme the quantum state can be tuned using only measurements.

2:30 pm -- 4:00 pm
Th4B • Session Th4B *(cont.)*
Presider: To be Announced

Th4B.3 • 3:30 pm Invited
Multi-photon Interference and Quantum Optical Interferometry, Christopher Gerry; *Dept. of Physics and Astronomy, Lehman College, The City Univ. of New York Bronx, USA*. We study multi-photon quantum interference effects at a beam splitter and its connection to the prospect of attaining interferometic phase shift measurements with noise levels below the standard quantum limit. Specifically, we consider the mixing of the most classical states of light, coherent states, with the most non-classical states of light, number states, at a 50:50 beam splitter. Multi-photon quantum interference effects from mixing photon number states of small photon numbers with coherent states of arbitrary amplitudes are dramatic even at the level of a single photon. For input vacuum and coherent states, the joint photon number distribution after the beam splitter is unimodal, a product of Poisson distributions for each of the output modes, but with the input of a single photon, the original distribution is symmetrically bifurcated into a bi-modal distribution. With a two-photon number state mixed with a coherent state a tri-modal distribution is obtained, etc. The obtained distributions are shown to be structured so as to be conducive for approaching Heisenberg-limited sensitivities in photon number parity based interferometry. We show that mixing a coherent state with even a single photon results in a significant reduction in noise over that of the shot-noise limit. Based on the results of mixing coherent light with single photons, we consider the mixing coherent light with the squeezed vacuum and the squeezed one-photon states and find the latter yields higher sensitivity in phase-shift measurements for the same squeeze parameter owing to the absence of the vacuum state. The squeezed one-photon state is identical to the one-photon subtracted squeezed state, and this motivates us to examine the prospect of using multiple photon-subtracted squeezed states for interferometry. We find that mixing coherent light with squeezed vacuum from which an odd number of photons have been subtracted would be especially efficacious for sub-standard quantum limit quantum optical interferometry.

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