Second International Conference on Optical Angular Momentum

3 – 5 June 2013
The Burrell Collection, Glasgow, UK

icoam2013.iopconfsd.org.

Image: Light profile with modal contributions of 2, 0, 1 and 3 units of orbital angular momentum; overlay of Rodin’s The Thinker, as displayed at the Burrell Collection.
FORTHCOMING INSTITUTE CONFERENCES
JUNE 2013 – JULY 2016

2013

3–5 June
Second International Conference on Optical Angular Momentum
The Burrell Collection, Glasgow, UK
Organised by the IOP Optical Group

24–26 June
Physics of Emergent Behaviour: From Single Cells to Groups of Individuals
The Grand Hotel, Brighton, UK
Organised by the IOP Biological Physics Group

8–12 July
International Conference on Neutron Scattering (ICNS2013)
Edinburgh International Conference Centre, Edinburgh, UK
Organised by the IOP Thin Films and Surfaces Group

3–6 September
Electron Microscopy and Analysis Group Conference 2013 (EMAG)
University of York, York, UK
Organised by the IOP Electron Microscopy and Analysis Group

4–6 September
PR’13: International Conference on Photorefractive Effects, Materials and Devices
The Winchester Hotel, Winchester, UK
Organised by the IOP Optical Group and the IOP Quantum Electronics and Photonics Group

9–11 September
Physical Aspects of Polymer Science
University of Sheffield, Sheffield, UK
Organised by the IOP Polymer Physics Group

16–18 September
Sensors & their Applications XVII
Rixos Libertas, Dubrovnik, Croatia
Organised by the IOP Instrument Science and Technology Group

16–19 September
EuroDisplay 2013 (33rd International Display Research Conference)
Imperial College London, London, UK
Organised by the IOP Optical Group and Society for Information Display

31 October – 1 November 2013
Topical Research Meeting: The Violent Universe
Institute of Physics, London, UK
Organised by IOP Astroparticle Physics Group

18–20 November
High-Speed Imaging for Dynamic Testing of Materials and Structures – 21st DYMAT Technical Meeting
Institute of Physics, London, UK
Organised jointly by the IOP Applied Physics and Technology Division and DYMAT Association

5–6 December
Electrospinning, Principles, Possibilities and Practice 2013
Institute of Physics, London, UK
Organised by the IOP Dielectrics Group and IOP Polymer Physics Group

12–13 December
Quantitative Methods in Gene Regulation II
Corpus Christi College, Cambridge, UK
Organised by the IOP Biological Physics Group

19 – 20 December
Institute of Physics, London, UK

2014

21–25 July
ICOSOS’11: 11th International Conference on the Structure of Surfaces
University of Warwick, Coventry, UK
Organised by the IOP Thin Films and Surfaces Group

2015

12–16 April
Electrostatics 2015
Southampton Solent University, Southampton, UK
Organised by the IOP Electrostatics Group

2016

11–16 July
The XXVII International conference on Neutrino Physics and Astrophysics
London, UK
Organised by IOP High Energy Particle Physics Group

See www.iop.org/conferences for a full list of IOP one-day meetings.

The conferences department provides a professional event-management service to the IOP’s subject groups and supports bids to bring international physics events to the UK.

Institute of Physics,
76 Portland Place, London W1B 1NT, UK
Tel +44 (0)20 7470 4800
E-mail conferences@iop.org
Web www.iop.org/conferences
## Contents

Welcome

Oral programme

Poster programme

Oral abstracts

Monday 03 June

Tuesday 04 June

Wednesday 05 June

Poster abstracts

<table>
<thead>
<tr>
<th>Section</th>
<th>Pages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welcome</td>
<td>2</td>
</tr>
<tr>
<td>Oral programme</td>
<td>3 - 6</td>
</tr>
<tr>
<td>Poster programme</td>
<td>7 - 9</td>
</tr>
<tr>
<td>Oral abstracts</td>
<td>10 - 26</td>
</tr>
<tr>
<td>Monday 03 June</td>
<td>10 - 13</td>
</tr>
<tr>
<td>Tuesday 04 June</td>
<td>13 - 19</td>
</tr>
<tr>
<td>Wednesday 05 June</td>
<td>20 - 26</td>
</tr>
<tr>
<td>Poster abstracts</td>
<td>27 - 47</td>
</tr>
</tbody>
</table>
Dear friends and colleagues,

It is our pleasure to welcome you to the second International Conference on Optical Angular Momentum, ICOAM 2013. We are delighted to be hosting this meeting at the iconic Burrell Collection of Glasgow. Just over three years have passed since the first ICOAM in York, which many of you will remember for its stimulating and exciting atmosphere. Since then, optical angular momentum research has both matured towards becoming a resource for photonic technology, imaging and communication applications, and expanded to the newly emerging field of electron vortices.

The idea to reunite the growing worldwide OAM community in a second conference arose at a meeting of the European research project Phorbitech (A Toolbox for Photon Orbital Angular Momentum Technology). The Phorbitech consortium was instrumental in the planning, organisation and sponsorship of this meeting.

Of course a successful meeting needs local organisers too and we sincerely thank Kirsty Orr and Claire Garland for their professional and friendly support of this conference. We have been fortunate to gain various sponsors in addition to the EU, including the Optical Group of the Institute of Physics (IOP), Scottish University Physics Alliance (SUPA), Boulder non-linear Systems, and the Glasgow University Optics Group.

We hope you all enjoy your stay in Glasgow and are inspired by the contributions and the atmosphere of our venue alike.

Sonja Franke-Arnold
Conference Chair, University of Glasgow, UK

Lorenzo Marrucci
University of Naples, Italy

Miles Padgett
University of Glasgow, UK
Oral programme

All talks are invited

Monday 3 June 2013

08:00 Registration and refreshments
09:10 Welcome and Introduction

Session 1: OAM phenomenology
Chair: S Barnett, University of Strathclyde, UK

09:20 (session introduction) Analogies between wave optics and quantum mechanics
G Nienhuis, Universiteit Leiden, Netherlands

09:50 What is spin to orbit angular momentum transfer?
I Fernandez-Corbaton, Macquarie University, Australia

10:10 Singular phase structure of nano-antenna system
M Coles, University of East Anglia, UK

10:30 Refreshments

11:00 Optical angular momentum and symmetries
R Cameron, University of Strathclyde, UK

11:20 Chiral electromagnetic fields
E Hendry, University of Exeter, UK

11:40 Five momenta
M Berry, University of Bristol, UK

12:00 Poster mini talks
13:00 Lunch

Session 2: Vortices in optical, electron and matter waves
Chair: D Andrews, University of East Anglia, UK

14:20 (session introduction) Peculiar rotation of electron vortices in magnetic fields
P Schattschneider, University Service Centre for Electron Microscopy, Austria

14:50 Generation and detection of OAM in electron beams
J Verbeeck, University of Antwerp, Belgium

15:10 Manipulation and detection of OAM in electron vortex beams
B McMorran, University of Oregon, USA

15:30 Refreshments
Controlling the handedness of laser resonators
A Forbes, National Laser Centre, South Africa

The physics of conserved quantities in classical electrodynamics
B Thide, Swedish Institute of Space Physics, Sweden

Radio applications of OAM states
F Tamburini, University of Padova, Italy

Poster mini talks

Drinks reception

Poster session part 1

Finger buffet

Poster session part 2

Tuesday 4 June 2013

Registration

Session 3: OAM toolbox (Phorbitech)
Chair: M Padgett, University of Glasgow, UK

(session introduction) Spiral photolithography of azopolymers
L Marrucci, Università di Napoli Federico II, Italy

Complete experimental toolbox for alignment-free quantum communication
F Sciarrino, Sapienza Università di Roma, Italy

Integrated vortex beam emitters
S Yu, University of Bristol, UK

'Twisted’ photon entanglement
W Löffler, Leiden University, Netherlands

Refreshments

Dimensionality in orbital angular momentum entanglement
M J Romero, University of Glasgow, UK

Biphoton optical vortices
S Walborn, Universidade Federal do Rio de Janeiro, Brazil

Quantum nature of radial degree of freedom of paraxial waves
E Karimi, University of Ottawa, Canada

High density atom traps using holographically shaped beams
N Radwell, University of Glasgow, UK

Experimental instability of higher-order optical vortices
M van Exter, Leiden University, Netherlands

Lunch
Session 4: Vector vortex beams and spin-orbit interactions of light
Chair: F Sciarrino, University of Rome, Italy

14:20  (session introduction) Transverse spin and momentum in evanescent waves
K Bliokh, RIKEN, Japan
14:50  Vector beams
G Milione, City College of New York, USA
15:10  Polarization patterns and singularities of Poincare beams
E J Galvez, Colgate University, USA
15:30  Optical and matter vortices and interactions
M Babiker, University of York, UK
15:50  Refreshments
16:20  Singularity and topological aberrations
J Götte, Max-Planck-Institute for the Physics of Complex Systems, Germany
16:40  Imprinting skyrmion spin textures in spinor Bose-Einstein condensates
Y Shin, Seoul National University, South Korea
17:00  Exploiting the angular momentum of light in nanophotonics
G Molina-Terriza, Macquarie University, Australia
18:00  Coaches depart from the Burrell Collection
18:30  Drinks reception and conference dinner (National Piping Centre)

Wednesday 5 June 2013

08:30  Registration

Session 5: OAM applications in imaging
Chair: B Boyd, University of Ottawa, Canada and University of Rochester, USA

09:00  (session introduction) Using OAM light for optical imaging
M Ritsch-Marte, Innsbruck Medical University, Austria
09:30  Quantitative spiral phase contrast imaging in a stimulated emission depletion microscope
M Guillon, Centre National de la Recherche Scientifique, France
09:50  On the generation and analysis of wave vortices
K Volke-Sepúlveda, Universidad Nacional Autonoma de Mexico, Mexico
10:10  Storage and non-collinear retrieval of optical angular momentum of light in cold atoms
L Pruvost, Centre National de la Recherche Scientifique, France
10:30  Refreshments and guided tour of the Burrell Collection
Session 6: OAM matter interaction
Chair: S Franke-Arnold, University of Glasgow, UK

11:30 (session introduction) Vortex beams and angular momentum of light
H Rubinsztein-Dunlop, University of Queensland, Australia

12:00 Structured light fields based on spiral beams – promoting photonic lattices and optical micromanipulation
C Denz, University of Münster, Germany

12:20 Twisted light in nanostructures
N M Litchinitser, The State University of New York, USA

12:40 Topological shaping of light by structured thin metal films
E Brasselet, Centre National de la Recherche Scientifique and University of Bordeaux, France

13:00 Lunch

Session 7: OAM applications in quantum information
Chair: L Marrucci, University of Naples, Italy

14:20 (session introduction) The Poincare sphere for OAM: variations on a theme
M Dennis, University of Bristol, UK

14:50 The duality relationship in the presence of post-selection
J Leach, Heriot-Watt University, UK

15:10 Playing with quantum states, playing with dimensions
J P Torres, Institut de Ciencies Fotòniques, Spain

15:30 Visualizing quantum state rotations through weak measurements of orbital angular momentum
M Malik, University of Rochester, USA

15:50 Refreshments

16:20 Real-time imaging of quantum entanglement
R Fickler, University of Vienna, Austria

16:40 More twists on optical twisters: of helicon-conical beams, superpositions and combinations
D Z Palima, Technical University of Denmark, Denmark

17:00 Close
Poster programme

**Topic: OAM phenomenology**

P.01 Experimental study of the cross-correlation function for partially coherent Laguerre-Gaussian beams
A Mourka, University of St. Andrews, UK

P.02 Optical angular momentum in conical diffraction
R Darcy, Trinity College Dublin, Ireland

P.03 Clebsch-Gordan coefficients for the addition of orbital angular momentum of Gaussian modes
M Dennis, Bristol University, UK

P.04 The role of vortices in the generation of optical lift (withdrawn)

P.05 Modal characterisation using principal component analysis: application to Laguerre-Gaussian beams and their superposition
A Mourka, University of St Andrews, UK

P.06 The forgotten quantum number: radial modes of Laguerre-Gauss beams
W Plick, Institute for Quantum Optics and Quantum Information, Austria

P.07 Do waves carrying orbital angular momentum possess azimuthal linear momentum?
F Speirits, University of Strathclyde, UK

**Topic: Vortices in optical, electron and matter waves**

P.08 Electron vortex propagation in magnetic fields
C Greenshields, University of Glasgow, UK

P.09 Chiral specific electron vortex beam spectroscopy
S Lloyd, University of York, UK

P.10 Subwavelength control of orbital angular momentum of light
G Parisi, Padova University and Laboratory of Nanofabrication of Nanodevices, Italy

P.11 Electron diffraction catastrophies
T C Petersen, Monash University, Australia

P.12 Instability of higher-order optical vortices
F Ricci, University of Padova, Italy

P.13 Experimental study of nanomanipulation of nanoparticles using electron vortex beams
J Yuan, University of York, UK

P.14 Angular momentum-dependent helicity transfer in nano-apertures
X Zambrana-Puyalto, Macquarie University, Australia

**Topic: OAM toolbox (Phorbitech)**

P.15 Photonic qudits and their applications in fundamental quantum mechanics and quantum information
V D’Ambrosio, Sapienza Università di Roma, Italy

P.16 Simulation of a spin polarization device in an electron microscope
V Grillo, S3-NANO CNR, Italy
Detection of a spinning object using light’s orbital angular momentum
M Lavery, University of Glasgow, UK

Nonlinear interpolation of OAM enhanced beam shifts
A Nugrowati, Leiden University, Netherlands

Method for direct measurements of the mean and variance of light OAM
B Piccirillo, Università degli Studi di Napoli, Italy

3D fluorescence imaging of laser beams
N Radwell, University of Glasgow, UK

Transverse Doppler Effect using optical beams with a twist
C Rosales-Guzmán, ICFO-Institut de Ciencies Fotoniques, Spain

Photoalignment-based liquid crystal q-plate technology
S Slussarenko, Università degli Studi di Napoli “Federico II”, Italy

Joining the quantum state of two photons into one
N Spagnolo, Sapienza Università di Roma, Italy

Controlled acceleration of superimposed higher-order Bessel beams
A Dudley, Council for Scientific and Industrial Research National Laser Centre, South Africa

Measuring Poynting vector of optical vortices using polarization interference
G Milione, City College of New York, USA

Optical angular momentum and phase conjugation (withdrawn)

Topology of dark tangles in light
A Taylor, University of Bristol, UK

Spatial correlation singularities of partially coherent fields
Y Yang, University of Electronic Science and Technology of China, China

Ince-Gaussian beams: manifold perspective in optical tweezers
C Alpmann, University of Münster and Institute of Applied Physics, Germany

Heralded single-photon ghost imaging utilising EPR correlations
R Aspden, University of Glasgow, UK

3D computational imaging via correlation measurement
B Sun, University of Glasgow, UK

Sub-Rayleigh optical vortex coronagraphy
E Mari, University of Padova, Italy

Optimising the use of detector arrays for measuring intensity correlations of photon pairs
D Tasca, University of Glasgow, UK
**Topic: OAM matter interaction**

**P.34** Propagation of high-intensive femtosecond vortex beams in media with focusing and inertial defocusing nonlinearities  
O Fedotova, Belarus National Academy of Sciences, Belarus

**P.35** Duality and beams of well-defined helicity: how to use them for experimental purposes  
I Fernandez-Corbaton, Macquarie University and 2 ARC Center of Excellence for Engineered Quantum Systems, Australia

**P.36** Light-matter angular momentum exchange in nanophotonic structures: beyond "spin" and "orbital" angular momentum  
R Oulton, Bristol University, UK

**P.37** Highly collimated source of cold Rb atoms from a 2–dimensional magneto-optical trap  
L Pruvost, Centre National de la Recherche Scientifique, France

**P.38** Classical and quantum regimes of collective orbital angular momentum exchange between light and ultracold atoms  
G Robb, University of Strathclyde, SUPA, UK

**Topic: OAM applications in quantum information**

**P.39** Fractional quantisation of optical angular momentum  
K Ballantine, Trinity College Dublin, Ireland

**P.40** Efficient quantum state reconstruction with mutually unbiased bases in high-dimensional orbital angular momentum subspaces  
D Giovannini, University of Glasgow, UK

**P.41** Imaging high-dimensional spatial entanglement with a camera  
M Edgar, University of Glasgow, UK

**P.42** Entanglement in 100 dimensions  
M Krenn, University of Vienna, Austria

**P.43** Gaussian entropy minimising states for orbital angular momentum and angular position  
A Yao, University of Strathclyde, UK
Oral abstracts

All oral presentations are invited

Analogies between wave optics and quantum mechanics

G Nienhuis
Universiteit Leiden, Netherlands

In quantum mechanics, a special role is played by systems with a Hamiltonian that is quadratic in its variables (coordinates and conjugate momenta). This is due to the fact that the equations of motion of the variables are linear. In this case, the correspondence between the quantum and classical description becomes particularly simple. A basis set of solutions in the quantum case is then directly obtained from the classical trajectories. These statements remain valid in the case of (classical) wave optics and its correspondence to ray optics. This sheds new light on the close relation between paraxial light beams and quantum harmonic oscillators. It also allows us to define various basis sets of shape-invariant beams of light.

What is spin to orbit angular momentum transfer?

I Fernandez-Corbaton
Macquarie University, Australia

When the phenomena referred to as spin-to-orbit angular momentum transfer in focusing and scattering are analyzed by means of symmetries and conservation laws, a surprising conclusion is reached. They are due to the breaking of two different fundamental symmetries: transverse translational symmetry in focusing and electromagnetic duality symmetry in scattering.

Singular phase structure of nanoantenna system

M Coles, M D Williams, K Saadi, D S Bradshaw and D L Andrews
University of East Anglia, UK

A family of nanoantenna systems with novel topology is shown, by exploiting the non-local nature of the photon, to permit delocalised electronic states whose relaxation produces optical fields with complex singular phase structure. This process takes advantage of the phase relationship between the quantum amplitudes relating to emission by different chromophores, a familiar concept in parametric nonlinear optics. To selectively produce fields with opposing circularity, it is shown that a number of important polarisation and symmetry conditions need to be satisfied. Comprehension of the physical picture is aided by plotting measures of spin and orbital angular momentum for the radiation generated by the array, and calculating recently discussed measures of helicity elucidates the chiral character of the systems. The generated radiation is shown to have spatially varying polarisation structure, and the features associated with it are examined. Furthermore, we consider the photonic nature of the radiation and the directed character of the emission; the findings represent a contribution to the ongoing debate over the amount of information potentially contained in a single photon. To further develop this method, practical considerations are discussed and potential new applications are identified.
Optical angular momentum and symmetries

R Cameron, S Barnett and A Yao
University of Strathclyde, UK, Scottish Universities Physics Alliance, UK

Ultimately, quantities like energy, linear momentum and angular momentum are important in Physics because they are conserved. In her well-known first theorem, Noether established a fundamental connection between conservation laws and symmetries in the laws of Physics. In my talk, I will discuss some of the types of angular momenta, in particular, that can be possessed by light and the symmetries inherent in Maxwell’s equations that underlie their conservation.

Chiral electromagnetic fields

E Hendry
University of Exeter, UK

We demonstrate the generation of short-range, chiral electromagnetic fields via the excitation of arrays of staggered nanoslits and nanoparticles that are chiral in two dimensions. The electromagnetic near fields, which exhibit a chiral density greater than that of circularly polarized light, can enhance the chiroptical interactions in vicinity of the nanoslits. We discuss the features of nanostructure symmetry required to obtain the chiral fields, and explicitly show how these structures can give rise to detection and characterization of materials with chiral symmetry.

Five momenta

M Berry
University of Bristol, UK

A tutorial talk, comparing five expressions for the local momentum in a wavefield. The expressions are equivalent but look different, emphasise different features, and give different insights.

Peculiar rotation of electron vortices in magnetic fields

P Schattschneider1,2, M Stöger-Pollach1, S Löffler1, Th. Schachinger2 and K Bliokh3

1University Service Center for Electron Microscopy, Austria, 2Institute of Solid State Physics, Austria, 3Usikov Institute of Radiophysics and Electronics, Ukraine

Free electrons with topological charge can now be produced in the electron microscope using computer generated holograms [1]. Recently, an astigmatic mode converter for vortex electrons that provides beams with almost tenfold intensity was demonstrated [2]. According to its high brightness, this technique opens an avenue for practical use of electron vortex beams. For instance, it has been proposed [3] that electron vortices are efficient probes for electron energy-loss magnetic chiral dichroism (EMCD) [4]. Numerical simulations show that this proposal is over-optimistic.

In order to better understand the physics of electron vortices and their inelastic interaction with matter, their propagation in fieldfree space [5], in a magnetic field, and in matter [6] is studied. Rich behaviour is found, showing peculiar rotation of vortex beams, significantly different from the well-known Larmor rotation in the lens field [7, 8]. These findings call for a reconsideration of imaging theory with magnetic lenses when vortex electrons
Generation and detection of OAM in electron beams

J Verbeeck
University of Antwerp, Belgium

In this talk we will discuss recent experiments with vortex electron beams. Different ways to produce such vortex states in an electron microscope as well as methods to detect the OAM of an arbitrary electron wave are discussed. The interaction of these charged vortex beams with the electrostatic potential of a crystal leads to the creation and annihilation of vortex/antivortex pairs which complicates the treatment of vortices inside a crystal considerably. Inelastic interaction of vortex electron waves delivers magnetic information possibly down to the atomic scale. Simulations and early experiments will demonstrate this.

Manipulation and detection of OAM in electron vortex beams

B McMorran
University of Oregon, USA

Here we discuss our experiments with electron vortex beams using nanofabricated optics. Under certain conditions electron vortex beams couple to matter much like polarized light, and our effort in using these beams to probe the electronic and magnetic properties in matter will be discussed. The electron vortex is a freely propagating electron in a quantized orbital state that can be used to gain fundamental insights into electrodynamics and evolution of quantum systems. We will discuss our investigations of states with high OAM quanta, superpositions of OAM states, measurements of the electron geometric phase, and addition and subtraction of OAM from vortex beams.

Controlling the handedness of laser resonators

A Forbes\textsuperscript{1}, D Naidoo\textsuperscript{2} and S Ngcobo\textsuperscript{2}

\textsuperscript{1}National Laser Centre, South Africa \textsuperscript{2}Council for Scientific and Industrial Research, South Africa

In this talk we consider the generation, in a controlled manner, of orbital angular momentum carrying beams from a laser resonator. We will outline simple techniques for creating superpositions of azimuthal modes through intra-cavity masks, and then will show an alternative approach to creating such modes through gain shaping. We show controlled generation of superpositions states up to very high order in the azimuthal index. Further, we show how to create single azimuthal modes through the use of intra-cavity optics that exploit the geometric phase of the light. Finally, we outline a new and robust means to execute these types of experiments with a digital laser.
The physics of conserved quantities in classical electrodynamics
B Thidé¹ and F Tamburini²

¹Swedish Institute of Space Physics, Sweden, ²University of Padova, Italy

Using OAM at low frequencies makes it possible to use radio techniques that can provide more detail than can be obtained with methods using diffractive optics element. This requires a thorough understanding of the fundamental physical properties of angular momentum and related physical observables and their measurement in experiments. We present some new results, based on classical electrodynamics, including a novel method of calculating the EM fields without the direct use of the Maxwell-Lorentz equations. This method has proved to be very efficient for numerical work and has the potential of significantly improve the speed of numerical simulations of OAM processes. A general overview of the use of OAM in radio science and technique will be presented.

Radio applications of OAM states
F Tamburini¹ and B Thidé²

¹University of Padova, Italy, ²Swedish Institute of Space Physics, Sweden

The discovery of astrophysical effects generating OAM might represent a new frontier for astronomy and general relativity. OAM, in the optical and infrared regime, are strongly affected by the atmospheric turbulence that makes OAM fingerprints in the radiation from celestial sources very difficult or almost impossible to detect and characterize. Certain radio frequencies have the possibility of bypassing this problem. Thus, we can use existing radio telescopes to detect OAM from extraterrestrial sources. We present some results from our experience in radio OAM.

Spiral photolithography of azopolymers
L Marrucci¹, A Ambrosio² and P Maddalena³

¹Università di Napoli Federico II, Italy ²CNR-SPIN, Italy

When a thin polymer film containing azobenzene moieties is illuminated with a patterned light field, stable reliefs and valleys appear on its surface, while keeping its total volume approximately constant, thus revealing a process of molecular migration induced in the material by the optical field. These polymer reliefs form patterns that are related in a non-trivial way to the illuminating field structure. The mass transport appears to occur preferentially in the direction of the electric field and to result from a sort of photo-induced fluidization of the material. These optical writing phenomena make azopolymers very attractive for optical data storage applications or for the nanoscale imaging of electromagnetic field distribution. Recently, the potential advantage of using azopolymers in the place of sacrificial photoresists in the fabrication of silicon micro- and nano-structures has also been demonstrated.

Despite a substantial research effort since the first discovery dated 1995, the microscopic mechanism underlying this phenomenon remains unclear. In this framework, we have recently reported the appearance of spiral-shaped relief patterns on the polymer under the illumination of focused vortex light beams [1]. The induced spiral reliefs are sensitive to the vortex topological charge and to the wavefront handedness. These findings are unexpected because the doughnut-shaped intensity profile of the writing vortex beams contains no information about the wavefront handedness.

To explain our observations, we have developed a model that links the main features of this phenomenon to the surface-mediated interference of the longitudinal and transverse components of the optical field [1,2]. The
interference pattern drives the molecular migration, via a photo-activated anisotropic random walk [2].


Complete experimental toolbox for alignment-free quantum communication

F Sciarrino¹, V D’Ambrosio¹, S P Walborn², L Aolita³, S Slussarenko⁴ and L Marrucci⁴
¹Sapienza Università di Roma, Italy, ²Universidade Federal do Rio de Janeiro, Brazil, ³Institut de Ciències Fotòniques, Spain, ⁴Università di Napoli ‘Federico II’, Italy

Quantum communication employs the counter-intuitive features of quantum physics for tasks that are impossible in the classical world. It is crucial for testing the foundations of quantum theory and promises to revolutionize information and communication technologies. However, to execute even the simplest quantum transmission, one must establish, and maintain, a shared reference frame. This introduces a considerable overhead in resources, particularly if the parties are in motion or rotating relative to each other. We experimentally show how to circumvent this problem with the transmission of quantum information encoded in rotationally invariant states of single photons. Our approach exploits multiple degrees of freedom of single photons. In particular, the polarization and transverse spatial modes stand out for this purpose. Just as the circular polarization states are eigenstates of the spin angular momentum of light, the helical-wavefront Laguerre-Gaussian modes are eigenmodes of its orbital angular momentum. By developing a complete toolbox for the efficient encoding and decoding of quantum information in such photonic qubits, we demonstrate the feasibility of alignment-free quantum key distribution, and perform proof-of-principle demonstrations of alignment-free entanglement distribution and Bell-inequality violation. The core of our toolbox is a liquid crystal device, named ‘q-plate’, that maps polarization-encoded qubits into hybrid polarization-OAM states of the same photon that are invariant under arbitrary rotations around the propagation direction, and vice versa. The scheme should find applications in fundamental tests of quantum mechanics and satellite-based quantum communication. Last results in this direction will be presented.

Integrated vortex beam emitters

M Thompson¹, X Cai¹, J Wang¹, M Strain², M Sorel², J O’Brien¹ and S Yu¹
¹University of Bristol, UK, ²University of Glasgow, UK

The generation, detection and manipulation of vortex beams of light carrying orbital angular momentum (OAM) has been restricted to bulk optical components such as spiral phase plates, q-plates or spatial light modulators. However, these bulk-optic approaches are typically slow to respond, cumbersome to use, and occupy a large footprint. Integrated photonic circuits on the other hand enables fast control, ultra-compact devices and complex optical circuits, and have revolutionized our ability to control and manipulate light at the micron-scale. Large-scale integrated photonic circuits are now possible, with circuits containing thousands of individual elements recently demonstrated [1].

For a scalable approach to the generation of OAM, the development of an integrated photonic vortex beam emitter is an appealing. Recent advances towards this goal include a mm-sized silicon photonic integrated circuit implementing a circular grating and capable generating free-space OAM [2]. Direct lasing emission of OAM has also been achieved using photonic crystal structures, generating radially polarized halo beams [3].
Here, we present a new concept (Fig 1) for the generation of optical vortex beams carrying OAM, based on micro-ring resonators, fabricated in silicon and suitable for large-scale integration. Our vortex beam emitter comprises a ring resonator integrated with a second order Bragg grating. The effect of the grating is to couple the rotating whispering gallery mode of the resonator to a free-space propagating vortex beam carrying OAM. We experimentally and theoretically demonstrate the OAM properties of the propagating beam, and show how different OAM states can be readily selected by simply tuning the wavelength of the injected light. Additionally, we fabricate arrays of these devices to demonstrate the scalability of this approach. The smallest device has a diameter of 8µm. This work opens up new research directions in OAM by exploiting recent advances in photonic integration. Our device provides an approach for realizing fast OAM switching and modulation (potentially at GHz speeds), and new possibilities in integrated quantum photonics. The large-scale integration nature of this technology could enable new micro-fluid and nanoparticle manipulation tools, such as lab-on-a-chip, optical tweezers and optical spanners.


**Twisted** photon entanglement

W Löffler¹ and B C Hiesmayr²

¹Leiden University, Netherlands, ²University of Vienna, Austria

The detection of entanglement in high-dimensional systems is challenging, for instance, there are entangled states where most known entanglement detection methods fail: bound entangled states. These are mixed entangled states where no operational entanglement distillation protocol is known. We show how these states can be synthesized in the lab using the OAM degrees of freedom of photons. We present a novel and conceptually simple method to detect entanglement, which is based only on complementarity of measurement bases. We demonstrate that the method is sensitive enough to even detect bound entangled states.

**Dimensionality in orbital angular momentum entanglement**

M J Romero¹, D Giovannini¹, S Franke-Arnold¹, S M Barnett², M J Padgett¹, C Yu³, J-D Bancal³ and V Scarani³

¹University of Glasgow, UK, ²University of Strathclyde, UK, ³National University of Singapore, Singapore

The information capacity of any communication system, classical or quantum, is limited by the number of orthogonal states in which the information can be encoded. Quantum key distribution and quantum computation have both been largely designed on the basis of qubits, such as the two-dimensional state space of photon polarisation. However, a photon is also endowed with other spatial degrees of freedom. In particular, it has been shown that photons generated via spontaneous parametric down-conversion (SPDC) are also correlated in their orbital angular momentum (OAM). Unlike polarisation, OAM resides in a theoretically infinite-dimensional, discrete state space. This promises a higher information capacity per photon, which may enable more complex quantum
computation protocols and more secure and robust forms of quantum cryptography. However, any practical experiment utilising the innately high-dimensional entanglement of OAM is subject to the modal capacity of the generation and detection systems, only a finite subset of the infinite-dimensional space is accessible experimentally. We show that the number of measured, entangled OAM modes in photon pairs generated by SPDC can be increased by tuning the phase-matching conditions in the SPDC process. We achieve this by tuning the orientation angle of the nonlinear crystal generating the entangled photons. We also show how we can guarantee the dimensionality of OAM entanglement, without any assumptions about the source (i.e. the generated two-photon state), relevant for device-independent quantum information.

Biphoton optical vortices
S Walborn¹, R Gomes², A Salles³, F Toscano¹ and P Souto Ribeiro¹

¹Universidade Federal do Rio de Janeiro, Brazil, ²Universidade Federal de Goiás, Brazil, ³Universidad de Buenos Aires, Argentina

Photons pairs that are entangled in orbital angular momentum (OAM) have been studied for over ten years. Typically, if one photon is detected with OAM equal to m, then the other will be found with OAM equal to -m. This correlation has been exploited extensively for the study of quantum entanglement and quantum information tasks, and is particularly interesting due to the larger Hilbert space dimension that is accessible. Here we describe the production of a distinct type of optical vortex that appears in the correlations of photon pairs, or biphotons. The vortex appears in a coordinate plane consisting of one cartesian coordinate of each photon. In this sense, neither photon alone possesses OAM, but when viewed together an optical vortex structure appears. We show that arbitrary-order vortices can be prepared by modifying the pump beam and non-linear crystal configuration in spontaneous parametric-down conversion. We also discuss the relationship between the winding number and entanglement and introduce an entanglement witness based on the phase structure.

Quantum nature of radial degree of freedom of paraxial waves
E Karimi
University of Ottawa, Canada

Photons possess transverse degrees of freedom: orbital angular momentum (OAM) and radial profile distribution beside the linear momentum and spin angular momentum (SAM). The light OAM received immense of attention in both classical and quantum regimes during past two decades. On the contrary, the radial degree of freedom of paraxial beam, e.g., in the Laguerre-Gauss basis, associated to the radial intensity and phase distribution of the light in the transverse plane has been out of interest almost completely. Nevertheless, these two transverse degrees of freedom, i.e., OAM and radial phase and intensity distribution, are strictly correlated. In fact, different OAM generators produce specific (and different) radial mode distributions. Unlike linear momentum and OAM photon eigenstates, the radial modes exhibit a more complicated structure, which render their manipulation less obvious. In this respect, to overcome the difficulties inherent to the radial profile of paraxial beams, a deeper understanding of the underlying symmetry is advisable. Such hidden symmetry, in fact, can be used to unveil novel and interesting features of the radial modes. Furthermore, beside the theoretical study, finding practical applications would make it much more interesting.

In my talk, I will discuss the hidden symmetry of radial degree of freedom of paraxial wave, and will also address new experimental achievements to unveil this “novel” feature in the quantum regime.
High density atom traps using holographically shaped beams

N Radwell, G Walker and S Franke-Arnold
University of Glasgow, UK

High-density ultracold atomic vapours have emerged as promising candidates for applications including quantum memories, high precision metrology, quantum simulations and quantum computation. Ever since the advent of atom trapping there has been a drive towards higher density systems. Standard magneto-optical traps (MOTs) have limits placed on the maximum densities achievable due mainly to re-radiation forces. This can be avoided in a dark spontaneous-force optical trap (dark SPOT) where the atoms in the core of the trap are sheltered from light forces. Here we demonstrate a technically simple technique which increases the density of the atoms by almost 2 orders of magnitude to $1.3 \times 10^{12} \text{ cm}^{-3}$ by using a dynamic dark SPOT. In contrast with previous realisations we can control the spatial and temporal profile of the laser beams. This allowed us to indentify an optimum size of the dark core which is 6 times larger than the MOT diameter which far exceeds the sizes used in all previous realisations. The increase in density results in a record phase-space density (PSD) since we avoid the unwanted heating which is often associated with compression methods. This technique could therefore be easily implemented in any system requiring a high PSD, with potential applications in efficient loading of optical dipole traps, as an efficient first stage to BEC, to benefit from collectively enhanced as well as nonlinear light-atom interactions and image storage.

Experimental instability of higher-order optical vortices

M van Exter, F Ricci and W Löffler
Leiden University, Netherlands

Higher-order optical vortices are inherently unstable in the sense that a single higher-order vortex that one expects to find in the dark region tends to split up in a series of vortices with unity charge. We experimentally demonstrate this vortex-splitting phenomenon in beams produced with holograms and spatial light modulators and discuss its generic and practically unavoidable nature.

To analyze the splitting phenomena in detail, we introduce a new technique to map the combined amplitude and phase profile of the optical field. This technique, which is based on the analysis of the far-field interference pattern observed behind an opaque screen perforated with multiple pinholes, turns out to be very robust and can among others be used to study very 'dark' regions of EM fields.

The measurement of vortex splitting provides an ultra-sensitive measurement method of unwanted scattering from holograms and other phase-changing optical elements like spatial light modulators. It also provides a natural way to quantify the purity of higher-order vortices. We are currently implementing techniques to improve this purity.

Transverse spin and momentum in evanescent waves

K Bliokh$^1$, A Bekshaev$^2$ and F Nori$^1$

$^1$RIKEN, Japan, $^2$II. Mechnikov National University, Ukraine

Momentum and spin represent fundamental dynamical properties of quantum particles. For photons, momentum is associated with the wave vector and is independent of polarization. In turn, spin is associated with a circular polarization and is also collinear with the wave vector. We show that situation becomes strikingly different for evanescent optical waves. First, evanescent waves possess momentum component, which depends on circular polarization and is orthogonal to the wave vector. Second, there is a spin angular momentum, which is largely independent of the polarization, and is also orthogonal to the wave vector. Although these extraordinary properties
seem to be in contradiction with what we know about photons, we show that they reveal a fundamental quantum
spin current hidden in propagating fields. Numerical calculations of the Mie scattering demonstrate that the
transverse momentum and spin push and twist an absorbing probe particle in an evanescent field, so that they can
be detected straightforwardly.

**Vector beams**

G Milione
City College of New York, USA

The conventional state of polarization of a light beam is spatially homogeneous - it is the same at every point in the
beam cross section. Yet, there exist states of polarization that are spatially inhomogeneous or vectorial - different at
every point. Such light beams are referred to as vector beams, two well known types being radial and azimuthal
polarization. In this presentation several unique properties of vector beams that contrast conventionally polarized
light beams will be discussed, specifically their intimate relationship to both light’s spin and orbital angular
momentum. This will be illustrated by their representation on a so called higher-order Poincare sphere, and their
ability to exhibit a spin and orbital angular momentum dependent Pancharatnam-Berry (geometric) phase.
Additionally, two new experiments will be presented - an analogy of the Stern-Gerlach experiment with vector beams
and a classical analogy of entanglement where vector beams play the role of Bell states.

**Polarization patterns and singularities of Poincare beams**

E J Galvez
Colgate University, USA

Collinear non-separable superpositions of spatial and polarization modes of optical beams result in rich polarization
patterns. The most interesting set of hybrid modes, involve Poincare modes, which contain single or multiple
mappings of the Poincare sphere onto the beam mode. These modes are ideal for studying polarization
singularities. We present an overview of our recent work and observations in searching for the space of parameters
that map all possible types of C-points, including monstars.

**Optical and matter vortices and interactions**

M Babiker
University of York, UK

Optical vortex physics is now a well-established and a growing branch of optics with a number of inter-disciplinary
connections and several applications. Recent advances, however, have led to the prediction and generation of the
electron vortex from an electron beam in an electron microscope. This is the first matter vortex with several key
properties additional to and distinct from those of the optical vortex. It is now clear that, in principle, any particle
vortex can be created from the corresponding matter beam using computer generated holographic methods and
there is scope for wide ranging variations in scale and parameters. This presentation highlights new developments
carried out by our group at York, together with collaborators, involving optical, electronic and atomic vortices [1-7].
Fundamental vortex properties, namely linear and orbital angular momentum content, spin and associated matter
fields as well as vortex multipolar interactions are discussed. Several features involving polarisation, particle spin
and orbital angular momentum exchange are highlighted.

Singularimetry and topological aberrations
J Götte¹ and M Dennis²

¹Max-Planck-Institute for the Physics of Complex Systems, Germany, ²University of Bristol, UK

We predict the splitting of a high-order optical vortex into a constellation of unit vortices, upon reflection or transmission of the carrier beam, and analyze the splitting [1]. The scattered vortex constellation generalizes, in a local sense, the more familiar longitudinal Goos-Hänchen and transverse Imbert-Fedorov shifts of the centroid of a scattered optical beam [2]. The centroid shift is related to the center of the constellation, whose geometry otherwise depends on higher-order terms in an expansion of the reflection matrix. We derive an approximation of the amplitude around the constellation as a complex analytic polynomial, the roots of which are the vortices. Increasing the order of the initial vortex gives an Appell sequence of complex polynomials, which we explain by an analogy with the theory of optical aberration. Determining the position of the optical vortices and thus the roots of the sequence of polynomials provides increasing information about the scatterer as the order of the initial vortex increases. We have termed this technique ‘singularimetry’ as an extension of optical polarimetry to the information contained in the spatial structure of the light.


Imprinting Skyrmion spin textures in spinor Bose-Einstein condensates
Y Shin
Seoul National University, South Korea

We present experimental demonstration of imprinting Skyrmion spin textures in a spinor Bose-Einstein condensate by rapidly moving the zero-field center of a 3D quadrupole magnetic field through the condensate. Various excitations such as 2D Skyrmions and coreless vortices were created in spin-1 sodium condensates, initially prepared in a uniform polar or ferromagnetic phase. The spin textures were characterized with the spatial distribution of the spin tilt angle, which is found to be in good quantitative agreement with the local description of single spins under the field rotation. Finally, we describe this field rotation method in terms of the spin-gauge potential derived from the spatially varying, quadrupole magnetic field.

Exploiting the angular momentum of light in nanophotonics
G Molina-Terriza
Macquarie University, Australia

In this talk I will present our latest experimental and theoretical results in the field of light-matter interactions at the nanoscale. We have studied how to control the modes of very small structures, such as cylindrical nano-holes in metallic films or small dielectric spheres, by exploiting the angular momentum modes of electromagnetic fields.
Second International Conference on Optical Angular Momentum

will present a couple of examples showing how analysing the scattering from nano-holes can help us retrieve information about the properties of the nano-structure. I will also explain how to understand some of the interaction of light with nanostructures by using the symmetries of the system.

**Using OAM light for optical imaging**

M Ritsch-Marte  
Innsbruck Medical University, Austria

An overview on the applications of OAM light in optical microscopy will be given. In Spiral Phase Contrast Microscopy, for example, a phase mask displaying an optical vortex gives rise to a doughnut-shaped point spread function, see Fig.1. Its effect is strong isotropic edge enhancement, since homogeneous areas of the sample appear dark due to destructive interference, whereas abrupt changes in a thin phase- or amplitude-object shift the phase difference more towards constructive interference. Assigning the central part of the vortex phase-mask a constant reference phase, self-referenced interference creates pseudo-relief images. Moreover, optically thick transparent samples lead to spiral fringes, which may be applied for phase demodulation from only a single image.

![Fourier transform](image)

**Fig.1: The principle of Spiral Phase Contrast**

**Quantitative spiral phase contrast imaging in a stimulated emission depletion microscope**

M Guillon, M Lauterbach, A Soltani and V Emiliani  
Centre National de la Recherche Scientifique, France

Recent experimental data demonstrating the straightforward implementation of spiral phase contrast (SPC) in a Stimulated Emission Depletion (STED) microscope are shown. For some applications, this additional SPC channel may circumvent the difficulty to dispose of more than one fluorescence channel in a STED microscope. SPC images of fixed and living neurones and astrocytes are registered in scanning mode and overlaid with super-resolved images. High contrasts obtained in this mode allow for quantitative phase delay measurements.

**On the generation and analysis of wave vortices**

K Volke-Sepúlveda  
Universidad Nacional Autonoma de Mexico, Mexico

Wave vortices are ubiquitous and, since their identification as a screw type wavefront dislocations by Nye and Berry in 1974 [Proc. R. Soc. A 336, 165–90 (1974)], the experimental generation of vortices in different kinds of wave fields has been a consistently pursued goal, with an increasing number of successful results over the years. Although nowadays, there are very well established methods for the generation of optical vortices, which have been
adapted to other kinds of waves as well, the generation technique is strongly determined by the wavelength regime. In this presentation, we will contrast some generation methods in different regimes, with special emphasis on light and sound waves. The additional degree of freedom provided by the polarization of light waves will be also considered for novel approaches in the generation of complex beams, which adds to the phase and intensity structure, the richness of polarization structure. Finally, the analysis of the generated wave fields also depends on the wavelength/frequency and the available instruments in each case; this issue will be discussed by means of some specific examples.

Twisted light in nanostructures
N M Litchinitser, J Sun, X Wang, J Zeng, M Shalaev, Z Kudyshev and A N Cartwright
The State University of New York, USA

Understanding the physics of the interaction of complex beams with nanostructured “engineered” media is likely to bring new dimensions to the science and applications of complex light, including novel regimes of spin-orbit interaction, extraordinary possibilities for dispersion engineering, and novel possibilities for nonlinear singular optics.

We report theoretical and experimental studies of linear and nonlinear interactions of complex light beams with orbital angular momentum with fiber-based magnetic and negative-index metamaterials and metasurfaces. In particular, our studies show that magnetic metamaterials can be used to manipulate complex polarization states, while negative index metamaterials can be used to manipulate the phase front of singular beams. We also predict that backward phase-matched process in negative index metamaterials with quadratic nonlinearity results in generation of backward propagating vortex beam with simultaneously doubled frequency and orbital angular momentum and reversed rotation direction of the wavefront. Finally, we discuss structured light propagation in indefinite optical metamaterials and propose several novel functionalities enabled by these strongly anisotropic structures, including beam intensity and wavefront shaping as well as transformations of orbital angular momentum. These studies may enable a new degree of freedom for multidimensional information encoding, novel mode conversion devices, and new phase-matching regimes for nonlinear optical frequency conversion processes.

Vortex beams and angular momentum of light
H Rubinsztein-Dunlop, D Preece, A Stilgoe and T Nieminen
University of Queensland, Australia

Light beams with phase singularities exhibit two related features: helical wavefront structures, and persistent dark spots, and applications potentially flow from each of these.

The dark spots find application in imaging and atom trapping, while the helical structures can carry information as classical bits or quantum qubits. The helical structures also carry optical angular momentum that can be used for manipulation of microscopic objects. Beams of light with phase singularities can be generated directly by lasers, or produced using phase plates or holograms and forms of tomography have been developed to detect and classify the singularities in a beam. The availability of spatial light modulators has allowed such applications to become more dynamic. The direct measurement of the orbital angular momentum in the beam especially for highly focused geometry is still rather difficult. Such beams differ from their non-paraxial counterparts due to a number of interesting effects most notably spin-orbital coupling. We investigate both theoretically and experimentally the actual torque applied to microscopic particles by beams with orbital angular momentum.
Optical tweezers can trap and move materials noninvasively at length scales ranging from tens of nanometers to tens of micrometers, and so have provided unprecedented access to physical, chemical and biological processes on a microscale. Since a light beam can carry angular momentum (AM) it is possible to use optical tweezers to exert torques to twist or rotate microscopic objects. Spin angular momentum depends on the degree of circular polarisation of the light, and orbital angular momentum depends on the spatial structure of the beam. If either the spin or orbital angular momentum is altered when the trapping beam is scattered by the particle in the trap, an optical torque will result.

Calculation of the optical torque directly can be rather difficult. The safest approach then is to determine the actual optical torque at the point of action. One method of doing this is to measure the applied force at a point. We measure displacement of a trapped particle in an assumed parabolic potential to determine the applied force at a point.

We create two optical potentials, the first is a strong Gaussian at 780 nm wavelength and the second a weaker Laguerre Gaussian beam at 1064nm. The beams have orthogonal polarisation. A 2 μm silica bead is trapped in the first potential. The time dependant position of the particle is measured via video microscopy. From this the measurement the stiffness of the trap is determined. The second beam in then introduced and the mean deflection that the introduction of this beam causes on the trapped particle is measured. The second beam is then moved and the process repeated in order to build up a two dimensional displacement map over the entire area of the Laguerre-Gaussian beam. This can then be converted to a 2 dimensional force map.

Structured light fields based on spiral beams – promoting photonic lattices and optical micromanipulation

C Denz, C Alpmann, A Kelberer, M Boguslawski, P Rose, M Woerdemann and W Horn
University of Münster, Germany

Spiral beams as Laguerre-, Ince-Gaussian or Bessel beams provide a variety of transverse beam profiles in combination with a characteristic propagation behaviour while carrying orbital angular momentum (OAM). These beams can be created by dynamic holographic beam shaping in different configurations, for example by real- or frequency-space holograms to create complex structured light fields. In our contribution, we will provide an overview of the highly topical field of complex beam shaping of these beams for applications in optical micromanipulation and photonic lattices. We will demonstrate different techniques of phase and/or amplitude modulation and discuss efficient generation of beam structures based on spiral beams.

Complex photonic lattices can be realized by exploiting spiral and other structured light fields to create refractive index changes in nonlinear optical, i.e. photorefractive materials. This technique, known as optical induction of lattices, leads to a structured photonic material, which can be ideally used to guide and steer light. In our contribution, we show the applicability of spiral beams to the creation of photonic lattices featuring conditions for stable propagation of optical vortex solitons. Additionally, we demonstrate superimposing multiple nondiffracting spiral beams to induce defect structures in two dimensional photonic lattices, permitting the propagation of defect modes inside the band gap.

In optical micromanipulation, spiral beams are used to transfer OAM to trapped particles, leading to a rotation on an orbit, depending on the charge and location of the beam’s singularities. Beside rotationally symmetric beams, especially elliptical beams as Mathieu or Ince-Gaussian beams are of interest, as their spatial distribution of singularities varies with increasing mode number. The combination of intensity and spatial OAM distribution leads eventually to non-uniform rotation of trapped particles. Beside OAM transfer from helical light to matter, helically shaped particles, as gears or spirals show rotational behavior in standard optical tweezers, as they can alter the flat
wave front of zeroth order Gaussian beams. In this context, we investigate the behavior of helical polymer-structures, which we create by femtosecond direct laser writing in SU8.

**Storage and non-collinear retrieval of orbital angular momentum of light in cold atoms**

L Pruvost¹, R de Oliveira², P Barbosa², D Felinto², D Bloch¹ and J Tabosa²

¹Centre National de la Recherche Scientifique, France, ²Universidade Federal de Pernambuco, Brazil

Light beams carrying orbital angular momentum (OAM) are of great interest because of their applications, ranging from the macroscopic particle manipulation to the encoding of quantum information. OAM beams are specified by a topological charge \( \ell \), and have a helical phase structure corresponding to the OAM per photon equal to \( \ell h/2\pi \). The nonlinear interaction of OAM beams with atomic systems via four-wave mixing (FWM) processes has demonstrated the OAM storage and the OAM conservation in the FWM process.

Differently from the previous observations, in this work we demonstrated that the stored OAM beam is retrieved along a non-collinear direction as shown in the figure. The experiment is performed in cold Cs atoms from a MOT, using a delayed FWM configuration with a writing beam W with topological charges \( \ell = 0, 1, 2, 3 \). The phase structure of W is stored into the Zeeman coherence grating induced by the incident writing beams \( W \) and \( W' \) and is restored when the reading beam R is switched on. The retrieved beam C is monitored by a CCD camera and shows the transfer and conservation of OAM.

**Topological shaping of light by structured thin metal films**

E Brasselet¹, G Gervinskas², G Seniutinas² and S Juodkazis²

¹Centre National de la Recherche Scientifique and Bordeaux University, France, ²Swinburne University of Technology, Australia

We report on the controlled generation of various sets of optical phase singularities from structured metalized substrates endowed with subwavelength features. Experimental demonstration of topological shaping of light in the visible domain will be presented and compared to predicted results. These findings might be useful towards the realization of small-scale singular optical elements having a large integration potential.

**The Poincare sphere for OAM: variations on a theme**

M Dennis

University of Bristol, UK

There are many analogies between classical and quantum phenomena in the theory of optical angular momentum. One of the most intriguing is the connection between the Bloch sphere for a quantum spin-1/2 system, the Poincare sphere for polarized light, and the 'Poincare sphere equivalent' for Hermite-Gauss and Laguerre-Gauss laser modes suggested by Padgett and Courtial in 1999, and its many generalizations which have been studied subsequently.

In this talk I will describe a slightly unusual approach based on quantization and group theory to these three spherical parameterizations of angular momentum, which leads to interesting generalizations involving the Majorana sphere for non-paraxial polarization, the analogues of the sphere for higher-dimensional orbital angular momentum bases, and determining properties of mode superpositions by singularimetry.
The duality relationship in the presence of post-selection
J Leach\textsuperscript{1}, E Bolduc\textsuperscript{2}, F M Miatto\textsuperscript{2}, G Leuchs\textsuperscript{3} and R W Boyd\textsuperscript{2,4}

\textsuperscript{1}Heriot-Watt University, UK, \textsuperscript{2}University of Ottawa, Canada, \textsuperscript{3}Max Planck Institute for the Science of Light, Germany, \textsuperscript{4}University of Rochester, USA

The duality relationship is one of the building blocks of quantum mechanics. Englert formally stated it as “The observation of an interference pattern and the acquisition of which-way information are mutually exclusive”. This principle has been put to the test many times, including Kwiat et al., who labelled each path of a Mach-Zehnder interferometer with polarisation to measure which-way information and the resulting interference pattern. In all of the experimental tests, the duality principle always prevailed. However, in a recent experiment, Menzel et al. conducted an experiment that reported high which-way information and high visibility fringes in a single experiment. They used pairs of photons entangled in position and momentum generated through spontaneous parametric down-conversion (SPDC) with a type II BBO crystal and an HG01 pump mode.

In this work, we investigate the duality relationship for light beams containing orbital angular momentum in the presence of post-selection. We investigate a two-dimensional subspace of OAM where different OAM states can be labelled with different polarisations. The coupling to the polarisation degree of freedom introduces a controllable non-separability between the mode’s internal degrees of freedom. This coupling gives the ability to report high “which-OAM” state and high “fringe visibility” measurements conditioned on successful post-selection of a particular polarisation. Our analysis highlights the importance of fair sampling in measurement procedures applied to the duality principle.

Playing with quantum states, playing with dimensions
J P Torres\textsuperscript{1}, M Hendrych, R Gallego, M Micuda, N Brunner and A Acin

\textsuperscript{1}Institut de Ciencies Fotoniques, Spain

Most photonic implementations of quantum ideas make use of the polarization degree of freedom. However, photons have a richer structure: they also have bandwidth and spatial shape, so they are intrinsically infinite dimensional objects. In this talk we will show how tailoring the overall form of photons (quantum state engineering), we can create quantum states in a space of arbitrary dimension, controlling even the classical/quantum nature of the states generated.

We will show results of a recent experiment where this is used to obtain information about the dimension of an unknown ensemble of quantum states (dimensional witness).

Visualizing quantum state rotations through weak measurements of orbital angular momentum
M Malik\textsuperscript{1}, M Mirhosseini\textsuperscript{1}, M P J Lavery\textsuperscript{2}, J Leach\textsuperscript{1,4}, M J Padgett\textsuperscript{2} and R W Boyd\textsuperscript{1,4}

\textsuperscript{1}University of Rochester, USA, \textsuperscript{2}University of Glasgow, UK, \textsuperscript{3}Heriot-Watt University, UK, \textsuperscript{4}University of Ottawa, Canada

Due in part to the no-cloning theorem, the measurement of a quantum state poses a unique challenge for experimentalists. Conventionally, a quantum state is measured through the indirect process of tomography, which requires significant post-processing times to reliably reconstruct the state. For this reason, quantum tomography is an unfeasible method for measuring high-dimensional quantum states such as those of orbital angular momentum. A novel alternative to quantum tomography was recently demonstrated in which the complex probability amplitude of a pure quantum state was directly obtained as an output of the measurement apparatus, bypassing the
complicated post-processing step required in tomography. In this method, the position of an ensemble of identically prepared photons was weakly measured, which caused a minimal disturbance to their momentum. A subsequent strong measurement of their momentum revealed all the information necessary to characterize their state in the continuous bases of position and momentum.

Here, we extend this novel technique to characterize a photon in the discrete, infinite-dimensional space of orbital angular momentum (OAM). This is achieved by expanding the individual components of the quantum state directly in terms of measurable OAM weak values. We measure each OAM weak value by performing a weak measurement of OAM and a strong measurement of angular position. The weak measurement of OAM is performed by first spatially separating the component OAM modes of our photon via an optical geometric transformation in combination with a beam-copying technique. Following this, we rotate the polarization of the OAM mode to be weakly measured by a small angle. After a strong measurement of angular position, the OAM weak value is obtained by measuring the changes in the photon polarization.

Using this method, we are able to directly obtain the probability amplitudes of a pure quantum state up to a dimensionality, $d=27$. More significantly, our method allows us to coherently measure the effect of rotations on a quantum state in the natural basis of OAM. Our work has strong applications in the field of quantum information as well as implications for foundational quantum mechanics.

**Real-time imaging of quantum entanglement**

R Fickler, M Krenn, R Lapkiewicz, S Ramelow and A Zeilinger

University of Vienna, Austria

Photonic entanglement of spatial modes is routinely studied in many experiments and offers interesting features for quantum optical and quantum information experiments. To investigate the properties of these complex modes, it is crucial to gain information about the transversal structure with high precision and in an efficient way. We show that modern technology, namely triggered intensified charge coupled device (ICCD) cameras are fast and sensitive enough to image in real-time the effect of the measurement of one photon on the spatial mode of its entangled partner photon. We determine from an imaged intensity pattern the number of photons within a certain region, evaluate its error margin and thereby quantitatively verify the non-classicality of the measurements. In addition, the use of the ICCD camera allows us to demonstrate visually the enhanced remote angular sensing and the high flexibility of our setup in creating any desired spatial-mode entanglement.

Supported by ERC (Advanced Grant QIT4QAD) and the Austrian Science Fund FWF (FoQuS Nr. F4006-N16 and CoQuS Nr.W1210-24007).

**More twists on optical twisters: of helico-conical beams, superpositions and combinations**

D Z Palima and J Glückstad

Technical University of Denmark, Denmark

We have previously demonstrated so-called optical twisters that can steer microparticles along spiral trajectories during optical micromanipulation. These optical twisters may be created using Fourier holograms of the helico-conical form, \( \exp \left( i l \theta (K - r_0) \right) \), which is characterized by non nonseparable helical or azimuthal phase and the conical or radial phase, and that have been shown to self-reconstruct after an obstruction. In this work, we deconstruct the helico-conical beam (HCB) as a coherent superposition of Bessel-like beams, which carry arbitrary topological charge. From this perspective, the HCB is seen as belonging to a generic family of beams that can be
generated using this type of superposition. Controlling this superposition enables us to generate tailored spiraling beams. We show different examples of such tailored beams, such as multi-helico-conical beams (i.e., helico-conical beam with selectable number of multiple helix) as well as multihelical beams that emulate the diffraction-free properties of its constituent Bessel-like beams.

Focal plane intensity distributions for different multihelical beams. The beams trace multiple helices as they rotate about the optical axis during propagation.

**P.01 Experimental study of the cross-correlation function for partially coherent Laguerre-Gaussian beams**

M Chen¹, Y Yang², M Mazilu¹, A Mourka¹, Y Liu² and K Dholakia¹

¹University of St Andrews, UK, ²University of Electronic Science and Technology of China, China,

Partially coherent light fields with embedded vortices exhibit fascinating properties and are important when considering propagation through turbulent media. It has been shown that phase correlation singularities denoting nulls of the cross-spectral density function are linked to the azimuthal degree of freedom – the azimuthal index of the field. The radial degree of freedom is usually neglected yet is a crucial facet for the complete description of the transversal state of a light field. It is thus important to understand this in relation to the CCF.

We experimentally study the CCF of partially coherent Laguerre-Gaussian (LG) beams. With the aid of a wavefront folding (WFF) interferometer, we measured the CCF of a partially coherent LG beam. Experimental results show the dependency of the far-field CCF on both the radial and azimuthal indices \((p, l)\) for a partially coherent light field. Fig. 1 on the poster shows examples of CCFs for partially coherent LG beams with \(l = 2, 4\) and \(p = 2, 4\). We found the number of dislocation rings in the far-field CCF is shown to be equal to \(2p + |l|\). This well-defined relationship is useful for the characterization of partially coherent fields with embedded vortices and higher order radial behaviour.

---

**P.02 Optical angular momentum in conical diffraction**

R Darcy, D O’Dwyer, C Phelan, K Ballantine, J Donegan, J Lunney and P Eastham

Trinity College Dublin, Ireland

Conical diffraction occurs when light is incident along the optic axis of a biaxial material. The light spreads out into a hollow cone within the crystal emerging as a hollow cylinder. A circularly-polarised beam becomes a superposition of two Bessel-like beams of zero and first order with a phase factor. This factor results in the formation of an optical vortex; there is a point of zero intensity around which the phase winds. Thus the beam carries orbital angular momentum.

Cascade conical diffraction occurs when more than one crystal is inserted into the light beam. For each additional crystal in the setup the maximum charge of the optical vortex may be increased by one. Mach-Zehnder interferometry is used to observe the optical vortices in conical beams and determine the charge of each vortex. Furthermore, the charge of the optical vortex can be selected using a combination of a circular polariser and circular analyser.

The polarisation at any point on the ring of conical diffraction is orthogonal to the polarisation at the antipodal point. Such a distribution implies the beam also carries spin angular momentum. This spin angular momentum may be converted to orbital angular momentum. When using elliptically polarised light, the orbital angular momentum of the beam may be tuned continuously between 0 and \(1\hbar\) per photon.
P.03 Clebsch-Gordan coefficients for the addition of orbital angular momentum of Gaussian modes
M Dennis and P Jones
University of Bristol, UK

Clebsch-Gordan coefficients are familiar from quantum mechanics as the amplitudes in mode decompositions of sums of angular momenta. In a real space representation on the sphere, they are given by the spherical harmonic mode coefficients of products of spherical harmonics.

Inspired by the well-known analogy between quantum spin and Gaussian modes, we consider Clebsch-Gordan analogues for products of Laguerre-Gaussian, Hermite-Gaussian and Generalized Gaussian modes. Physically, they correspond to the decomposition of two modes under parametric up-conversion. Our analysis shows that the Clebsch-Gordan coefficients for Gaussian modes depend on the polar angle on the orbital angular momentum Poincaré sphere, unlike their quantum angular momentum analogues. This is interpreted in terms of the hidden SU(2) symmetry of 2-dimensional quantum harmonic oscillators and Gaussian laser modes.

P.04 The role of vortices in the generation of optical lift
S Hanna¹, G Swartzlander² and S Simpson¹
¹University of Bristol, UK, ²Rochester Institute of Technology, USA

When a linearly polarised plane wave is incident on a semi-cylindrical lightfoil, an optical “lift” force may be generated, which has many potential applications including the driving of micromachines, biological transport or improved designs of solar sails for interstellar space travel [1,2]. The lightfoil also experiences an optically induced torque until it reaches a stable orientation. Torque generation and lift are associated with the production of optical phase singularities, which change in position and number as the orientation of the lightfoil is changes relative to the incident wave, and as the symmetry and chirality of the lightfoil is altered. In this paper we examine the link between the formation of phase singularities and the generation of mechanical torque and lift in such systems, using a combination of analytical and computational approaches.


P.05 Modal characterization using principal component analysis: application to Laguerre-Gaussian beams and their superposition
A Mourka¹, M Mazilu¹, E M Wright² and K Dholakia¹
¹University of St Andrews, UK, ²The University of Arizona, USA

Laguerre-Gaussian (LG) modes are circularly symmetric transverse laser modes that possess a phase factor exp(ilφ), where φ is the azimuthal angle. These beams are characterized by two mode indices. The radial index p can take any non-negative integer value and determines the radial shape, or node number, of the light distribution. The azimuthal index (or topological charge) l indicates the number of 2π phase changes that the field displays around one circumference of the optical axis. This gives rise to an on-axis optical vortex. The LG modes may carry orbital angular momentum (OAM) that can be defined as lℏ per photon. Due to this property, they find a variety of applications in widespread fields such as optical manipulation, microfluidics, free-space communication and quantum entanglement. The determination of the OAM content in these light beams is an important issue. It is to be noted that such modes of light are rarely found in pure azimuthal index states; rather the light field will be optimally
described by both mode indices, I and p. Thus, it would be very advantageous to measure both mode indices using one measurement. Recent studies have reported a new method for the simultaneous determination of the constituent azimuthal and radial mode indices for light fields possessing OAM. The method is based upon probing the far-field diffraction pattern from a random aperture and using the recorded data as a 'training' set. Subsequently we can transform the observed data into uncorrelated variables using the principal component analysis (PCA) algorithm. Our PCA detection method is generic and may be extended to superpositions of different families of light fields. Additionally, beam superpositions of LG beams can be experimentally decomposed delivering the intensity and relative phases of each mode. Here, the amplitudes of the different LG components in a superposition of LG beams were measured. Thus, this approach represents a powerful method for characterizing the optical multi-dimensional Hilbert space, which will be useful for many applications relating the optical technologies, such as the modal decomposition for optical fibers, laser resonators and information processing.

P.06 The forgotten quantum number: radial modes of Laguerre-Gauss beams
W Plick, M Krenn, R Fickler, R Lapkiewicz, S Ramelow and A Zeilinger
Institute for Quantum Optics and Quantum Information, Austria

The orbital angular momentum quantum number of Laguerre-Gauss beamshas received an explosively increasing amount of attention over the past twenty years. However, often overlooked is the so-called radial number of these beams. We present for the first time the quantum formalism of this "forgotten" quantum number, as well as its physical interpretation, including its conjugate variable and uncertainty relations.

P.07 Do waves carrying orbital angular momentum possess azimuthal linear momentum?
F Speirits and S Barnett
University of Strathclyde, UK

All beams are a superposition of plane waves, which carry linear momentum with no azimuthal component. However, plane waves incident on a hologram can produce a vortex beam that carries orbital angular momentum and has a well-defined non-zero azimuthal momentum component. We solve this apparent contradiction by showing that the azimuthal component of the momentum is not a true linear momentum and the azimuthal wavevector $k \phi$ emerges from the interference of the complex amplitudes of the incident plane waves.

Topic: Vortices in optical, electron and matter waves

P.08 Electron vortex propagation in magnetic fields
C Greenshields, R Stamps and S Franke-Arnold
University of Glasgow, UK

While vortices and orbital angular momentum have been studied for many years now in optics, and vortex electron states are seen in condensed matter, it is only recently that electron vortices in free space were first theoretically predicted and then observed. These electron vortices have the same geometrical properties as their optical counterparts, however there are significant differences too, for instance unlike photons electrons have charge and mass, and half-integer spin. Of particular interest are the magnetic properties resulting from the circulation of electronic charge, which have no analogue in optics. Using the Schrödinger equation we investigate the interaction of electron vortices with an external magnetic field, and this allows us to reinterpret known behaviour of electrons in terms of vortex states and orbital angular momentum [1]. Applications are anticipated in electron
microscopy, where vortex beams could lead to imaging with new magnetic sensitivity.


P.09 Chiral specific electron vortex beam spectroscopy
S Lloyd, J Yuan and M Babiker
University of York, UK

Recent advances in electron microscopy have led to the experimental realisation of electron vortices - helical electron beams that carry well defined orbital angular momentum. The orbital angular momentum lends these beams chiral features, which make them potentially useful as probes of chiral materials, notably those with magnetic properties. This presentation outlines the use of electron vortex beams in electron energy loss spectroscopy to investigate chiral materials.

In examining the interaction of electron vortex beams with chiral matter, we focus first on the interaction of the vortex beam with atomic matter, and extend this treatment to consider the implications for condensed matter systems. Under certain conditions the interaction proceeds via the same mechanism as magnetic circular dichroism, usually probed with x-rays. This special case arises when the axis of symmetry of the interacting system coincides with the beam axis. We show that, outside of these particular circumstances, treatment of the interaction requires careful consideration of the extrinsic nature of the orbital angular momentum of the electron beam and the strength of the interaction, so as to relate changes in the OAM of the beam and the chiral material.

P.10 Subwavelength control of orbital angular momentum of light
G Parisi
Padova University and Laboratory of Nanofabrication of Nanodevices, Italy

We performed three-dimensional finite elements simulations of the optical response of holey plasmonic vortex lenses, i.e., spiral grooves milled on a thin gold film with a hole at the center. We focus in particular on the properties of the wave transmitted in the underlying half-space, which is shown to be a relevant part of the transmitted field. We find out that the angular momentum selection rule for this part of the field is different from the one for the transmitted plasmonic vortex, although closely related to the plasmonic interaction of the impinging wave with the chiral geometry.

P.11 Electron diffraction catastrophes
T C Petersen, M Weyland, D M Paganin, T P Simula, S A Eastwood and M J Morgan
Monash University, Australia

Experimental measurements and investigations of phase vortices were recently reported in electron optics, such as the observation of a forked dislocation in an off-axis electron hologram by Uchida and Tonomura [1]. Interest in this emerging field of singular electron optics continues to grow with work reported in Nature [1, 2] and Science [3]; demonstrating that it is possible to produce and control electron vortex beams, including those with high orbital angular momentum (OAM). Electron vortex manipulation continues to advance with further development of micron sized grating structures [4, 5].
Phase singularities have been studied extensively in light optics [6, 7], matter waves [8] and x-ray optics [9]. In particular, structurally stable configurations of optical vortices have been investigated by Berry et al. [10], who showed that optical caustics are not sharp, as predicted by geometrical optics, but have a fine structure arising from diffraction, which can be described using catastrophe theory [11]. In our recent work on electron diffraction catastrophes [12], we produced distorted lattices of electron vortices by imposing aberrations in a transmission electron microscope (TEM). Following ideas from light optics [13], we also created probes with substantial OAM density, without recourse to high order topological charges. Topological features such as nodal line configurations and vortex loops were studied using in-line holography along with experimental measurements of the probability density within focal volumes of aberrated lenses.

Our current interests are focused upon exploring the elementary electron diffraction catastrophes further; to examine Airy folds, Pearcy [14] cusps and the elliptic umbilic etc. Our experiments utilize a particular aberration corrected TEM (Titan™ 80-300 TEM (FEI) at the Monash Center for Electron Microscopy), which can correct both the illumination and imaging lenses. These dual sets of lenses allow the variation of catastrophe state variables as well as control space variables. By varying higher order aberrations in the imaging lenses, we can access higher order catastrophes and more elaborate configurations of structurally stable electron vortices. Such patterns could find application in electron holography, based upon structured illumination. Indeed, our initial motivation for producing electron diffraction catastrophes was prompted by a form of three-beam vortex-lattice holography, in which the displacement of phase vortices is used to measure the thickness distribution of refracting objects [15].

Figure 1: through-focal volume of the electron wave probability density measured in the TEM. For this hyperbolic umbilic catastrophe, 52 experimental images were stacked along the vertical (optical) axis and interpolated to create the false-colour tomogram. The topmost front corner has been cropped by slicing through the curved Airy fold surface to reveal the umbilic focus and diffraction detail, which acts as a skeleton [11] for the electron diffraction catastrophe.
Figure 2: two sections of the elliptic umbilic electron diffraction catastrophe, induced by higher-order probe-forming aberrations and unfolded using the aberration-corrected imaging lens focus.


P.12 Instability of higher-order optical vortices
F Ricci¹, W Löffler² and M van Exter²
¹University of Padova, Italy ²Leiden University, Netherlands

We provide experimental and theoretical proof that higher-order optical vortices are intrinsically unstable. Being very susceptible to field perturbations, the main vortex tends to split up into singly charged optical vortices, giving rise to a fine structured dark region in the core of the singular beam. We describe three different experimental methods to study this vortex-splitting phenomenon, the first two being based on intensity and phase maps of the vortices respectively; while the third one is based on the analysis of the far-field interference pattern behind a screen where a set of multiple pinholes are symmetrically arranged over a circle. We show that this device, a multi-pinhole interferometer, turns out to be a powerful tool to study very ‘dark’ regions of electromagnetic fields and to provide a local decomposition of arbitrary optical fields in the basis of orbital angular momentum states. Finally, we also provide a theoretical framework that explains this vortex-splitting phenomenon, revealing its practically unavoidable nature.

P.13 Experimental study of nanomanipulation of nanoparticles using electron vortex beams
J Yuan, G Thirunavukkarasu, K McKenna and M Babiker
University of York, UK

Electron beams possess non-zero angular momentum have attracted much attention in recent years since their realization in transmission electron microscopes. These beams have possible applications in spectroscopy, manipulation and trapping of nanoparticles etc. In this study, we focus on the experimental study of manipulating gold nanoparticles. The experiment had been conducted in a JEOL 2200FS double-aberration corrected TEM.
operating at an acceleration voltage 200kV, which utilizes a specially designed condenser mask aperture with a fork dislocation to produce the required vortex electron beams. The motion of the nanoparticle under vortex beam illumination is examined by video capturing and analysing individual frames of images. We show unambiguous evidence for the rotation induced in the nanoparticle to be correlated to the chirality of the electron vortex beam. However, detailed examination of the induced rotation shows sign of stochastic processes, indicating the rotation is dissipative.

**P.14 Angular momentum-dependent helicity transfer in nano-apertures**

X Zambrana-Puyalto, X Vidal and G Molina-Terriza

Macquarie University, Australia

The field of the angular momentum (AM) of light has been quickly expanding since the seminal contribution of Allen and co-workers in 1992 [1]. It is used in optical tweezers to rotate particles and drive micro-rotors [2], in quantum communication to create multidimensional entangled states [3] and in astrophysics to detect exotic cosmic objects [4]. In contrast, the helicity of light has been overlooked and often confused with the spin of light [5]. It has not been until very recently that its importance in the light-matter interactions and its connection to Maxwells generalized duality symmetry in material media has been recently revealed in [6].

In this work, we probe rounded nano-apertures drilled in a 200nm gold layer with light beams with a well-defined \( z \) component of the AM (\( J_z \)) and helicity. Our laser is a tunable diode laser working at the near infra-red. Then, on one hand, a Spatial Light Modulator (SLM) is used to give the adequate twisting phase to the light beams and on the other hand a set of waveplates is used to project the beam into the chosen helicity state. The beam is focused with an x20 Microscope Objective, and the light is collected with a different x100 one, imaging the scattering of the nanohole onto a CCD camera. Before the light reaches the CCD chip, a set of waveplates and a linear polarizer project the light into a well-defined state of helicity. We study the transfer of helicity, i.e. the ratio between the light scattered in the two orthogonal helicity components, depending on the AM and the helicity of the incident beam. We find that there is not a trivial relation between the transfer of helicity and the \( J_z \) of the incident beam. In particular, the two orthogonal modes with \( J_z = 0 \) have an anomalous high transfer. We link this phenomenon to the symmetries of our system.


**Topic: OAM toolbox (Phorbitech)**

**P.15 Photonic qudits and their applications in fundamental quantum mechanics and quantum information**

V D’Ambrosio and F Sciarrino

Sapienza Università di Roma, Italy

High dimensional quantum systems have opened new scenarios in several fields like fundamental quantum mechanics in which they can be exploited to perform contextuality tests, quantum communication since a d-dimensional system can carry much more information than a two dimensional one and quantum cryptography
where they can be exploited to increase the security. Moreover they can be used as a tool to check the dimension of a system by constructing dimensional witnesses. An efficient way to realize qudits (quantum d-dimensional systems) is by exploiting different degrees of freedom of single photon like polarization, path and orbital angular momentum (OAM). In this framework OAM in particular is a fundamental resource since it is defined in an infinite dimensional Hilbert space and can be used alone or in combination with other degrees of freedom (hybrid approach) for qudits encoding. By exploiting hybrid encoding based on OAM and photon polarization we performed a task in which quantum mechanics provides an advantage over classical theories and no hypothetical post-quantum theory can do it better. This advantage has been experimentally demonstrated both in a state dependent and a state independent way based on Kochen-Specker sets. Another application of hybrid qudits have been the experimental realization of a non extendible set of mutually unbiased bases in dimension six. These bases are strictly correlated to the concept of complementarity and are a fundamental resource for quantum state tomography.

P.16 Simulation of a spin polarization device in an electron microscope

V Grillo¹, L Marrucci², E Karimi³, R Zanella⁴ and E Santamato²

¹S3-NANO CNR, Italy, ²Università di Napoli “Federico II”, Italy, ³University of Ottawa, Canada, ⁴Laboratory for Technologies of Advanced Therapies, Italy

A proposal for an electron-beam device that can act as an efficient spin-polarization filter has been recently put forward [E. Karimi et al., Phys. Rev. Lett. 108, 044801 (2012)]. It is based on combining the recently developed diffraction technology for imposing orbital angular momentum to the beam with a multipolar Wien filter inducing a sort of artificial non-relativistic spin-orbit coupling. Here we reconsider the proposed device with a fully quantum-mechanical simulation of the electron beam propagation, based on the well-established multi-slice method, supplemented with a Pauli term for taking into account the spin degree of freedom. Using this upgraded numerical tool, we study the feasibility and practical limitations of the proposed method for spin-polarizing a free electron beam.

P.17 Detection of a spinning object using light's orbital angular momentum

M Lavery¹, F Speirits², S Barnett² and M Padgett¹

¹University of Glasgow, UK, ²University of Strathclyde, UK

In recent years, consideration has been given to the use of orbital angular momentum in imaging and remote sensing, where the detection of the angular momentum may reveal the structure or potentially the motion of the object [1-5]. Here we will report that, when light is scattered from a spinning object, the rotation rate of the object can be measured by analysing frequency shifts in the orbital angular momentum of the light.

The linear Doppler shift is widely used to infer the velocity of approaching objects, but this shift does not detect rotation. By analysing the orbital angular momentum of the light scattered from a spinning object we observe a frequency shift many times greater than the rotation rate. This rotational frequency shift is still present when the angular momentum vector is parallel to the observation direction, i.e. when the linear Doppler shift is zero. Our findings, including the multiplicative enhancement of the frequency shift, have applications in both terrestrial and astronomical settings for the remote detection of rotating bodies.

P.18 Nonlinear interpolation of OAM enhanced beam shifts
A Nugrowati and H Woerdman
Leiden University, Netherlands

We have studied the effect of non-integer Orbital Angular Momentum (OAM) on OAM enhanced beam shifts, for in-plane (Goos-Haenchen) and out-of-plane (Imbert-Fedorov) shifts. Contrary to naive expectation we find, theoretically and experimentally, that the non-integer OAM beam shifts do not interpolate linearly between the integer OAM beam shifts.

P.19 Method for direct measurements of the mean and variance of light OAM
B Piccirillo, S Slussarenko, L Marrucci and E Santamato
Università degli Studi di Napoli, Italy

A newly conceived method is introduced for measuring simultaneously both the mean and the variance of the orbital angular momentum distribution in any paraxial optical field avoiding the measurement of the exact angular momentum spectrum. This method enables to reduce the infinitely many output ports required to perform an ideal spectrum analysis to only two ports, one for the mean and one for the variance. Therefore it provides access to the mechanical torque that the optical field in any light beam could exert on matter and could be exploited to weaken the strict alignment requirements usually imposed by traditional schemes for OAM-based free-space communications.

P.20 3D fluorescence imaging of laser beams
N Radwell, M Boukhet, T Clark and S Franke-Arnold
University of Glasgow, UK

Laser beams with non-trivial intensity structure have uses in several areas of physics such as optical tweezers and atom trapping. Measurement of the full 3D intensity structure of such beams would typically involve taking several transverse images of the beam along its propagation direction, which is slow and destructive, making imaging of counter propagating beams impossible. Here we present a method of measuring the complete 3D intensity distribution of a laser which can be fast, non-destructive and have high resolution. The technique is based on fluorescence from an atomic vapour providing 2D projections of the beam, which we then rotate along its axis to detect many projections. Tomographic reconstruction then provides the full 3D intensity distribution. To demonstrate this method we produce several superpositions of Laguerre-Gaussian beams, chosen for their interesting transverse profiles and compare with the ideal case. We can then reduce the noise inherent in tomography by background subtraction, made possible by the fixed camera position.
P.21 Transverse Doppler Effect using optical beams with a twist
C Rosales-Guzmán1, N Hermosa1, J Torres1 and A Belmonte2
1ICFO-Institut de Ciencies Fotoniques, Spain, 2Technical University of Catalonia, Spain

We present a new way to detect the velocity of scatterers moving in a plane transverse to the direction of the propagation of a beam, using engineered beam profiles such as those embedded with Orbital Angular Momentum (OAM).

In the classical nonrelativistic Doppler scheme, only the longitudinal component of the movement of a particle, i.e. the velocity along the direction of propagation of the light, is measured. The transverse velocity cannot be detected readily. However, the use of light beams with spatial structure (Optics Letters 36, 4437, 2011) allows measurement of the transverse component of the velocity of the particle. The main point in using structured light is that the light scattered by a particle at its particular location is associated to a specific value of the phase of the incident field. The particle produces an echo that is dependent on the phase of the incident field as it moves across the beam. By noting the change of the phase of the echo (Doppler Effect), the movement can be measured.

One of the simplest beams with defined phase gradient is the family of Laguerre-Gaussian beams (LG). As one encircles the simplest LG beam with index n at a particular propagation distance, the phase follows a gradient from 0 to 2*pi*n. It is therefore ideal to use these beams to determine a particle's rotational movement that is perpendicular to the propagation of the beam. We will show initial results that we have obtained from our experiments.

Any type of transverse movements can be detected in a similar manner however the spatial shape of the light beam should be changed to match the particular characteristics of the movement.

P.22 Photoalignment-based liquid crystal q-plate technology
S Slussarenko, B Piccirillo, L Marrucci and E Santamato
Università degli Studi di Napoli “Federico II”, Italy

An important prerequisite for almost any successful application of light beams carrying orbital angular momentum (OAM) stands in our ability to generate a desired photon state and subsequently manipulate it. In case of OAM, this is strongly correlated with our ability to control the wave front of the beam. Numerous techniques for this purpose were developed and implemented during the last twenty years, such as holograms, spiral phase plates, mode converters, uniaxial and biaxial crystals and others. Each of them has its own advantages and disadvantages in terms of flexibility, quality, price and complexity.

A different approach to beam wave-front shaping was implemented recently, in which the needed phase change is obtained by introducing a transversely inhomogeneous geometrical phase. In the visible and infrared light domains, this has been realized thanks to the so-called “q-plates” – liquid crystal wave plates having an inhomogeneous optical axis orientation with a nonvanishing topological charge q in their center. The geometrical-phase working principle enables not only the simple generation of helical beams, but also the spin-to-OAM conversion, the polarization control of the output OAM state, the preparation of spin-orbit single-photon entanglement, the generation of vector beams and other features that cannot be implemented easily with conventional methods. Thanks to their properties and ease of use, q-plates found place in numerous experiments of quantum and classical optics.
Here we present a survey of the state-of-the-art photoalignment-based q-plate technology. By introducing the liquid crystal photoalignment technique into the q-plate fabrication process, it was possible to go much beyond the initially realized circular q-plates with unit topological charge. Devices able to generate beams with high OAM values, different OAM superpositions and other phase structures are available nowadays.

P.23 Joining the quantum state of two photons into one

N Spagnolo¹, C Vitelli¹, L Aparo¹, F Sciarrino¹, E Santamato² and L Marrucci²

¹Sapienza Università di Roma, Italy, ²Università di Napoli “Federico II”, Italy

Quantum computation promises a great enhancement of the computational power at our disposal. To turn this vision into a reality, the greatest challenge is to substantially increase the amount of information – the number of qubits – that can be processed simultaneously. In photonic approaches, the number of qubits can be raised by increasing the number of photons. This is a fully scalable method, in principle, but in practice it is limited to 6-8 qubits by the present technology. An alternative approach is that of using an enlarged quantum dimensionality within the same photon, for example by combining different degrees of freedom, such as polarization, time-bin, wavelength, propagation paths, or transverse modes. Although not scalable, the latter approach may allow for a substantial increase in the number of qubits. Ideally, one would therefore like to combine these two methods and be able to switch from one to the other, depending on the specific needs. However, since photons do not interact, multiplexing and demultiplexing the quantum information across photons has not been possible hitherto. In our work, we propose and experimentally demonstrate a quantum process, named “quantum joining”, in which two arbitrary qubits initially encoded in separate input photons are combined into a single output photon, within a four-dimensional quantum space. The process can be iterated, to join a larger number of qubits, and hence may be used to bridge multi-particle protocols of quantum information with the multi-degree-of-freedom ones. The quantum joining may also find application in interfacing multiple photonic qubits with a matter-based quantum register, another crucial element of future quantum information networks.

Topic: Vector vortex beams and spin-orbit interactions of light

P.24 Controlled acceleration of superimposed higher-order Bessel beams

A Dudley¹, C Schulze², F S Roux¹, M Duparré² and A Forbes¹

¹CSIR National Laser Centre, South Africa, ²Friedrich Schiller University, Germany

In this work we present a mechanism for generating superpositions of non-canonical, higher-order Bessel beams, which are characterized by the anisotropy of the optical vortex on the propagation axis, known as the morphology parameter. We implement a spatial light modulator to create superimposed, non-canonical, higher-order Bessel beams and a CCD camera positioned on a translation stage to investigate the propagation of the resulting field. It is already known that the intensity profile of the resulting field experiences an angular rotation. However, we show that by tuning the morphology parameter, the rate of rotation will change periodically as a function of the propagation distance. Apart from demonstrating the controlled angular acceleration of the resulting intensity profile, we also experimentally and theoretically show the transfer of energy between accelerating and decelerating sections in the intensity profile. The experimentally produced fields are in good agreement with those calculated theoretically.
P.25 Measuring Poynting vector of optical vortices using polarization interference

V Kumar and N Viswanathan
University of Hyderabad, India

Optical singularities recognized as the skeleton of electromagnetic fields is rapidly becoming an important tool for sensitive measurement of amplitude, phase, polarization and their variations [1]. Light beams carrying spin and orbital angular momentum possess finite transverse component of Poynting vector. We propose a novel technique for the measurement of transverse component of Poynting vector using polarization interference. The appearance of well-defined polarization singularities (C-point and L-line) in 2D fields is exploited for extracting the phase structure of the optical vortex beam and is extended for generalized anisotropic (non-canonical) vortex of any vortex charge.

As the Poynting vector is proportional to the phase gradient [2], the measurement of ellipse orientation around a polarization singular point can effectively be used for the measurement of phase structure around phase singularity and hence the Poynting vector distribution in the beam cross-section.

Polarization singular C-point surrounded by lemon or star polarization ellipse pattern is formed due to the superposition of orthogonal circularly polarized Laguerre-Gauss (LG0l) and Gaussian beams [1, 3]. The phase variation around the phase singularity is twice that of the ellipse orientation variation around the polarization singularity resulting in $\pi l$ to $2\pi l$ mapping. We present our experimental measurements of the ellipse orientation around a C-point using spatially-resolved Stokes polarimetry and use it for calculating the phase and Poynting vector distribution and hence the orbital angular momentum density of optical vortices.


P.26 Optical angular momentum and phase conjugation (withdrawn)

P.27 Topology of dark tangles in light

A Taylor and M Dennis
University of Bristol, UK

Many physical systems exhibit quantised vortices, around which some field parameter winds an integer number of times. We investigate the geometry of these vortices via large scale numerical simulation of an optical random wave model.

On the large scale, vortices can form complex tangles that defy analytic description. We make use of subtle measures like the probabilities of knotting and linking to quantify their behaviour. As the model is very general, the results have implications for comparison both with other optical models and with vortex structures in other physical systems.
P.28 Spatial correlation singularities of partially coherent fields
Y Yang, N Luo and Y Liu
University of Electronic Science and Technology of China, China

Recently, the coherence vortices and the phase singularities of a partially coherent have been studied by Optical coherence theory, and the cross correlation function of a partially coherent beam has been studied theoretically and experimentally. It has been shown that spatial correlation functions have interesting topological properties associated with their phase singularities, and there exist correlation singularities (denoting nulls of the cross-correlation function) in the regions where the phase is ill-defined. Here analytical and numerical investigations are made in the far field based on the mutual coherence function. We show there are many kinds of correlation singularities in partially coherent optical field besides cross-correlation singularity, and the correlation singularities can even exist in the partially coherent field without OAM.

Topic: OAM applications in Imaging

P.29 Ince-Gaussian beams: manifold perspective in optical tweezers
C Alpmann¹, C Schöler², M Woerdemann² and C Denz²
¹University of Münster and Institute of Applied Physics, Germany, ²University of Münster, Germany

Solutions of the Helmholtz equation provide a great variety of spiral beams as Laguerre-, Ince-Gaussian or Bessel beams. All of them combine complex transverse beam profiles with characteristic propagation behaviour while carrying orbital angular momentum (OAM). Besides solutions in Cartesian and polar coordinates, especially solutions in elliptical coordinates suggest promising future applications as they already include the former classes and are therefore more general. In optical tweezers’ applications, these beams can be created by dynamic holographic beam shaping in form of frequency-space holograms. We demonstrate different techniques of phase and /or amplitude modulation, discuss efficient generation of beam structures based on spiral beams and their combinations and will provide an overview of the highly topical field of complex beam shaping. As the spatial distribution of singularities varies in elliptical Mathieu or Ince-Gaussian beams with increasing mode number, the combination of intensity and spatial OAM distribution may result in a non-uniform rotation of trapped particles. The broad range of existing transverse intensity distributions of even, odd and helical modes, offers an amount of remarkable possibilities, wherefrom we will show characteristic configurations. We report the generation of complex elliptical light formations and their application as optical light moulds, which use the ability of light, to carry its shape to matter by light-material interaction. Especially Ince-Gaussian beams offer a new potential in optical micromanipulation and might arise a wide spreading interest comparable to Hermite- or Laguerre-Gaussian beams, which makes them highly attractive for interdisciplinary applications.

P.30 Heralded single-photon ghost imaging utilising EPR correlations
R Aspden¹, D Tasca¹, R Boyd² and M Padgett¹
¹University of Glasgow, UK ²University of Ottawa, Canada

It is well known that the photon pairs from spontaneous parametric down-conversion (SPDC) possess strong spatial correlations. These correlations are present both in the image plane and far-field of the down-conversion source: a realisation of Einstein-Podolsky-Rosen (EPR) type correlations in the transverse spatial degrees of freedom of the photon pairs.
In 1995, these spatial correlations were used in the first demonstration of a ghost-imaging system. In single-photon ghost imaging, one of the photons generated in SPDC is incident on an object before being detected by a non-spatially resolving “bucket” detector. The other photon in the pair is incident on a spatially resolving detector, and the image is obtained from the coincidence counts. All previous implementations of single-photon ghost-imaging systems have relied on a scanning detection system, with an inherent detection efficiency scaling with the inverse of the number of pixels in the image. We overcome such limitations by using an intensifying CCD (ICCD) camera to measure the spatial distribution of the single photons across the full scene. We obtain our coincidence counts by triggering our ICCD using the signal obtained from the bucket detector. To account for the electronic delay in the triggering mechanism, a 22m free space, image preserving delay line was built prior to the camera. The use of an ICCD camera allows the full-field detection of the spatial distribution of the single photons. We obtain high-contrast, low-background images, enabling the demonstration of EPR correlations between the photon pairs in a multi-mode configuration. Our images contain approximately 500 distinguishable spatial states, corresponding to 9 bits of information per detected photon. This creates opportunities for its use in investigations of quantum information protocols.

**P31. 3D computational imaging via correlation measurement**

B Sun, M Edgar, R Bowman, L Vittert, S Welsh, A Bowman and M Padgett

University of Glasgow, UK

Computational ghost imaging is a branch of classical ghost imaging, which retrieves spatial information of a scene by the correlation of thermal speckles. In classical ghost imaging a series of changing speckles are sent through a beam splitter and each speckle is separated into two twin beams. One beam interacts with the object and the intensities are collected by a single-pixel detector, whereas on the other beam the speckle patterns are detected by a CCD camera. Then the correlation of the object light intensities and the corresponding speckle patterns reconstructs the object. Computational ghost imaging simplifies the system by utilising a computer controlled spatial light modulator, which negates the requirement of the CCD and the beam splitter, since the speckle patterns can be predicted by the hologram. Therefore measurement in computational ghost imaging is between a real beam and a virtual one.

In our computational ghost imaging experiment setup we employ a digital light projector as the speckle generator and several photodiodes in different position. The projector generates binary structure light patterns onto the object. The scattered light is collected by photodiodes in different position. Each detector gives a 2D reconstruction of the 3D real-life reflective object. All 2D images have the same shape but different intensity distribution (shading). It is realised in our work that the shading of a ghost image is determined by the detecting vector (pointing from the object to the detector) and the object surface. Therefore by comparing the shading of multiple 2D ghost images we are able to reconstruct the 3D profile of the object. Our 3D ghost imaging system consisting of a light projector and four photodiodes promises reasonable 3D reconstruction even compared with a commercial 3D imaging system based on multiple cameras.

**P32. Sub-Rayleigh optical vortex coronagraphy**

E Mari, F Tamburini, GSwartzlander, A Bianchini, C Barbieri, F Romanato and B Thidé

1University of Padova, Italy, 2Rochester Institute of Technology, USA, 3Swedish Institute of Space Physics, Sweden

We introduce a new optical vortex coronagraph(OVC) method to determine the angular distance between two sources when the separation is sub-Rayleigh. We have found a direct relationship between the position of the minima and the source angular separation. A priori knowledge about the location of the two sources is not required.
The superresolution capabilities of an OVC, equipped with an \( l=2 \) N-step spiral phase plate in its optical path, were investigated numerically. The results of these investigations show that a fraction of the light, increasing with N, from the secondary source can be detected with a sub-Rayleigh resolution of at least 0.1 \( \lambda/D \).

**P.33 Optimising the use of detector arrays for measuring intensity correlations of photon pairs**

D Tasca\(^1\), M Edgar\(^1\), F Izdebski\(^2\), G Buller\(^2\) and M Padgett\(^1\)

\(^1\)University of Glasgow, UK \(^2\)Heriot-Watt University, UK

Spatial states of paraxial photons have found applicability in many quantum information protocols such as cryptography, communication, information processing and teleportation.

On one hand, the utilisation of photonic spatial degrees of freedom enables the access to a large state space, bringing advantages to quantum information processing and fundamental investigations of quantum mechanics. On the other hand, the analysis of optical modes in the single photon regime is predominantly performed by means of a scanning procedure, which makes it extremely demanding as the dimension of the state space increases. Then, the benefit introduced by the use of a large state space depends on one’s ability to perform a multi-mode analysis of the photon state.

In this work we describe the use of multi-element detector arrays in the measurement of multi-mode spatial correlations of photons. With the advance of the modern detector arrays, especially single-photon sensitive cameras, multi-mode coincidence detection of the photon pairs is becoming a more attractive alternative than the traditional scanning detection systems. Whilst the noise level in these cameras is still higher than in the traditional single-photon avalanche diodes, it is already low enough to enable coincidence detection in SPDC experiments. We analyse the measurement of intensity correlations of the photons in a multi-mode configuration in the presence of noise, and provide the optimal conditions for obtaining maximum visibility of the measured correlation function in terms of the detector parameters and on the mean number of detected modes. We experimentally test our theoretical predictions by utilising an electron multiplying CCD camera to measure spatial correlations of the photon pairs from SPDC, finding an excellent agreement with our theoretical analysis. We expect the use of detector arrays to become an important technique for accessing the full transverse field of photon pairs, creating new possibilities for the investigation of two photon entanglement and in application to quantum information protocols.

**Topic: OAM matter interaction**

**P34. Propagation of high-intensive femtosecond vortex beams in media with focusing and inertial defocusing nonlineairties**

O Fedotova\(^1\), O Khasanov\(^1\), G Rusetsky\(^1\) and T Smirnova\(^2\)

\(^1\)Belarus National Academy of Sciences, Belarus \(^2\)International Sakharov Environmental University, Belarus

We investigate the propagation of high-intensive femtosecond singular pulsed beams in Kerr medium at different topological charges, ratio of initial pulse power to critical one and group velocity dispersion (GVD). For the first time the role of inertial origin of plasma formation providing stable propagation of the femtosecond vortices is analyzed. Vortex beam stability against azimuthal perturbations was elucidated. The vortex beam pass through the sample with the inertial as well as the instantaneous plasma nonlinearity has been considered. Comparison of results obtained allows us to reveal plasma inertia impact on vortex pulsed beam stability in medium. For given topological charge \( m \) the initial conditions were chosen as the doughnut pulsed beam perturbed by 5% amplitude random noise. For \( m=1 \) and input pulse power \( P \sim 9P_{cr} \), where \( P_{cr} \) is critical power value for self-
focusing the vortex travels in medium with instantaneous plasma nonlinearity over the distances larger than two diffraction lengths $L_{df}$ before undergoing 2-3 azimuthal modulations. At distances $L \sim 3L_{df}$ and more the energy between filaments is redistributed but total angular moment is conserved, what may originate from the vortex structure. Later the filaments become unequal in intensity and some of them dominate.

Numerical calculations of the azimuthal modulational instability of vortices with regards of the inertial nature of plasma have confirmed our assumptions about its stabilizing influence. The simulations for fused silica have shown that plasma inertia provides the vortex stability at larger distances $L \sim 3.75L_{df}$ before it starts to break up into filaments.

The vortices with larger topological charge obey the similar scenarios but the distances of vortex stability are essentially shorter. The vortex behaviour is such that in addition to $(2m+1)$ bright filaments, weaker ones coalesce at the center of singularity at larger scales and gradually decline.

It is established, that for shorter pulse durations, when GVD becomes more essential, the filamentation process under conditions of normal GVD includes reshaping temporal profile of the vortex and splitting ring structure in three subrings in radial direction. Outer and inner subrings of almost equal intensity still retain the original shape of vortex. Reshaping is observed in central part of doughnut ring. Under vortex propagation filaments are originated in the central ring, and less intense peripheral rings disappear.

We have searched for the solution in the form of the optical bullet on the base of variation approach under anomalous GVD conditions.

P35. Duality and beams of well-defined helicity: How to use them for experimental purposes
I Fernandez-Corbaton
Macquarie University and ARC Center of Excellence for Engineered Quantum Systems, Australia

Light matter interactions can be studied within the framework of symmetries and conservation laws. The use of duality symmetry and its conserved quantity, helicity, makes this approach simple yet powerful [1]. This conservation law, which is independent of the geometry of the problem, completely determines whether the momentum space polarisation of a beam can or cannot change after its interaction with a scatterer. The application of such framework allows to understand the root causes of the phenomena commonly referred to as “spin to orbital angular momentum transfer” in focusing and scattering. The “spin to orbit” label is actually masking two completely different root causes: breaking of transverse translational symmetry in focusing and breaking of duality symmetry in scattering. The use of the framework in practical experimental situations is quite straightforward. I will illustrate this by using Bessel beams of well defined helicity to analyze the different stages of an archetypal experiment like the one in the figure by means of symmetries and conservation laws.

P36. Light-matter angular momentum exchange in nanophotonic structures: beyond "spin" and "orbital" angular momentum

R Oulton1, A Thijssen1, I Luxmoore2, N Wasley3, L K Kuipers4, D Beggs4, A Ramsay5, SKasture6, V Achanta6, A M Fox3 and M Skolnick3

1Bristol University, UK, 2University of Exeter, UK, 3University of Sheffield, UK, 4AMOLF, Netherlands, 5Hitachi Cambridge Laboratory, UK, 6Tata Institute for Fundamental Research, India

The exchange of angular momentum between photons and "artificial atoms", quantum dots (QDs), is key to many quantum information protocols. QDs are solid-state quasi-two-level systems, where information may be transferred between the spin of a single electron and a single photon. Strict selection rules dictate that angular momentum must be preserved in the optical transition. Usually, the photon is conceived as being in an arbitrary superposition of circular polarization states. To increase the light matter interaction strength, the QDs are embedded into nanophotonic structures, where the paraxial description of light no longer applies. In particular, photonic crystal nanocavity and waveguide structures exhibit complex polarization-dependent variation in the local light density of states (LDOS). The transfer of angular momentum in these structures is no longer trivial. The small (>>λ) QD experiences a modified LDOS particular to its exact position, but it emits a photon in an entire photonic mode. In order to transmit a quantum of angular momentum, or indeed an arbitrary superposition of momenta, one requires the nanophotonic structure to possess several properties. The LDOS at the QD position should allow equal coupling to any superposition state, whilst the photon mode should support superposition states.

At present, a description (beyond simple linear polarization) of the LDOS and mode angular momentum in these structures, let alone interactions with quantum emitters, is almost non-existent. However, it is likely that this description will go beyond "spin" and "orbital" angular momentum of light. Nevertheless, novel behaviour is already emerging. We will discuss a variety of nanophotonic structures containing QDs. We will show that even simple structures, such as a cross-waveguide show counterintuitive behaviour of the emission, due to an interaction between QD position in the structure and its spin[1]. We will also show that in photonic crystal waveguide structures, QDs placed at strategic "C-points"[2] show a direct electron spin to propagation direction conversion. Such a device could easily form a key element in an integrated quantum optical chip. Finally, I will discuss how real photonic crystal cavities designs may be analysed for their suitability to couple QD spin angular momentum to light[3].

Highly collimated source of cold Rb atoms from a 2-dimensional magneto-optical trap

L Pruvost\(^1\), V Carrat\(^1\), C Cabrera-Guiterez\(^1\), M Jacquey\(^1\), J Tabosa\(^2\) and B viaris de Lesegno\(^1\)

\(^1\)Centre National de la Recherche Scientifique, France, \(^2\)Universidade Federal de Pernambuco, Brazil

Using a blue-detuned laser shaped in a Laguerre-Gaussian donut mode we highly collimate the output of a 2-dimensional magneto-optical trap. The resulting atomic beam has a 1 mm diameter, its divergence is reduced from 40 down to 3 mrad and the atomic density is increased by a factor of 200. The collimation effect has been studied versus the order \(\ell\) of the Laguerre-Gaussian mode (up to 10) and the laser detuning (2-120 GHz).

The “2D-colli-MOT” study allows us to determine the best conditions which minimize the atom heating due to residual light absorption and optimize the collimation effect. We will describe the experimental setup, the procedure, the obtained results and will show how the 2D-colli-MOT could provide a new tool to load a 3D-MOT using lasers with millimeter range diameters and thus sparing the laser power.

Classical and quantum regimes of collective orbital angular momentum exchange between light and ultracold atoms

G Robb

University of Strathclyde, SUPA, UK

In recent years various collective nonlinear interactions between light and cold atoms/Bose-Einstein Condensates (BEC) have been observed experimentally e.g. Collective Atomic Recoil Lasing (CARL) [1-3], Superradiant Rayleigh Scattering [4] and Kapiza-Dirac scattering [5]. A common feature of these interactions is the development of spontaneous density modulations in the atomic gas as a result of interaction with a dynamic optical potential which is generated and amplified by the atoms themselves via a collective instability.

To date, the collective atom-light interactions studied have involved only plane-wave optical beams with linear momentum and the interactions have involved collective exchange of linear momentum between atoms and optical fields. Extending the concept of collective instabilities as described above to interactions involving exchange of Orbital Angular Momentum (OAM) may lead to new nonlinear optical processes involving OAM, generation of helical density modulations in cold gases and the production of persistent currents in BECs [6].

An analysis of collective instabilities involving Laguerre-Gaussian (LG) beams interacting with a gas of ultracold atoms will be presented [7]. The interactions will involve the transfer of OAM between the optical fields and the atoms through dynamic dipole forces. Conditions for the existence of collective instability and the consequent spontaneous formation of azimuthal or helical density modulations will be derived for two regimes: a classical regime where many atomic OAM states are populated and OAM exchange between light and atoms can be described as a continuous process, and a quantum regime in which only two atomic OAM states participate and the discreteness of the OAM exchange between light and atoms is significant.

Beams of light can carry both spin angular momentum, $S$, associated with the polarization, and orbital angular momentum, $L$, associated with the angular dependence of the phase. For uniformly polarized beams with rotationally symmetric intensity profiles the spin, orbital, and total angular momentum of a photon are conserved and are integer multiples of Planck’s constant. Thus these quantities provide a discrete state space which can be probed in quantum optics experiments and may be useful for encoding quantum information. We derive the conservation laws and quantization conditions in more general cases where the polarization varies across the beam, using beams generated by conical diffraction in biaxial crystals as examples. The conserved angular momentum of such polarization textures derives from their symmetry under combined rotations of polarization and phase, and is a general linear combination $L$ and $S$ which can be measured interferometrically. We calculate the shot noise in the associated angular momentum current, and hence identify the quantum of angular momentum in such beams.

The orbital angular momentum (OAM) of light provides a practical degree of freedom for encoding quantum information in higher-dimensional alphabets. The characterization of high-dimensional OAM quantum states can however prove difficult as the dimension $d$ of the OAM subspace considered increases. In fact, while it is possible to reconstruct the density matrices of entangled bi-photon states using appropriate overcomplete sets of tomographic measurements, the number of measurements does not scale favourably with $d$. We overcome this limitation by employing mutually unbiased bases (MUBs) to determine the density matrix with fewer measurements than ordinary quantum state tomography (QST), and with comparable fidelity. It is difficult to define MUBs for a large-dimensional system, both because of theoretical limitations and practical reasons connected with the experimental implementation of a complete high-dimensional set of MUBs. We therefore reconstruct the density matrix of an entangled two-photon state by performing local measurements in superposition states belonging to single-qudit MUBs, in the single-photon regime. We show experimentally that efficient complete quantum state tomography of a high-dimensional multipartite quantum system can be performed with exactly the minimum number of measurements by considering only the MUBs of the individual parts (D. Giovannini et al., Phys. Rev. Lett. 110(14):143601, 2013), whose state spaces are always smaller than the state space of the composite system.

The light produced by parametric down-conversion shows strong spatial entanglement that leads to violations of EPR criteria for separability. Historically, measurements of EPR correlations have been performed using high-
sensitivity, single-element single photon detectors that must be scanned across the detection planes to establish these correlations. In this work, we show that modern electron-multiplying CCD cameras possess sufficiently high sensitivity and adequately low background that they can be used to measure intensity correlations directly across a multi-pixel field of view. Employing this technology we observe entanglement of around 2500 spatial states and the strength of the correlations is sufficient to demonstrate EPR-type correlations by more than two orders of magnitude. More generally, our work shows that cameras can lead to important new capabilities in quantum optics and quantum information science.

**P.42 Entanglement in 100 dimensions**

M Krenn¹, M Huber², R Fickler¹, R Lapkiewicz¹, S Ramelow¹ and A Zeilinger¹

¹University of Vienna, Austria, ²ICFO-Institut de Ciencies Fotoniques, Spain

Entangled quantum systems have properties that have fundamentally overthrown a classical worldview. Increasing the complexity of entangled states by expanding their dimensionality not only allows the implementation of novel fundamental tests of nature [1-2], but also enables genuinely new protocols for quantum information [3]. Spatial modes of photons are a vivid field of research, as they provide a source for high-dimensional entanglement readily available from down-conversion [4-8].

We present an experiment that determines the dimensionality of two-photon entangled state. The photons are created in spontaneous parametric down-conversion, and we use the “full-field” Laguerre-Gauss basis to analyze the photons. To examine high-dimensional entanglement, we develop a novel state-independent entanglement witness. The witness is capable of unambiguously revealing high dimensional entanglement through sub-space correlations.

In the experiment, we analyze a (186*186)-dimensional Hilbert space. With only ~210,000 projective measurements, we were able to demonstrate 100-dimensional entanglement. This result indicates the great potential of high-dimensional entangled systems for various quantum information tasks.

P.43 Gaussian entropy minimizing states for orbital angular momentum and angular position

A Yao\textsuperscript{1}, T Brougham\textsuperscript{1}, E Eleftheriadou\textsuperscript{1}, M Padgett\textsuperscript{2} and S Barnett\textsuperscript{1}

\textsuperscript{1}University of Strathclyde, UK, \textsuperscript{2}University of Glasgow, UK

We propose well-behaved states for angular position and orbital angular momentum (OAM) which have a lower uncertainty product than the intelligent states, both for the “usual” angle-OAM uncertainty relation and for the entropic relation. As these states are convenient to work with, both analytically and experimentally, we suggest that they are the optimal states to use for quantum information purposes.
Proceedings are an important part of the scientific record, documenting and preserving work presented at conferences worldwide. *IOP Conference Series™* offers a fast, efficient, and cost-effective proceedings service.

**Visibility**
Papers are widely indexed and *IOP Conference Series* receives more than 2.3 million article downloads per year.

**Flexible publication**
From plenary to poster papers, large or small events, core physics to multidisciplinary, we can accommodate all.

**IOP Proceedings License**
Authors retain copyright. No forms for organizers to administer, substantially reducing their workload.

**Fast publication**
Proceedings are published within 4–6 weeks after IOP Publishing receives the accepted articles.

**Prepublication approval**
Organizers log into our prepublication servers to check and approve their proceedings prior to online publication.

**Conference promotion**
For selected events, we can provide highly targeted promotion at no extra cost.

Visit [conferenceseries.iop.org](http://conferenceseries.iop.org) for details of publishing options, and much more.