Symposium Interactions between Twisted Light and Particles (SYTL)

jointly organized by
the Atomic Physics Division (A) and
the Quantum Optics and Photonics Division (Q)

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Overview of Invited Talks and Sessions

(Lecture room: C/gHS)

Invited Talks

SYTL 1.1	Fri	11:00–11:30	C/gHS	**Optical curl forces and beyond** — •Michael Berry
SYTL 1.2	Fri	11:30–12:00	C/gHS	**Quantum memories for twisted photons** — •Elisabeth Giacobino, Julien Laurat, Dominik Maxein, Lambert Giner, Lucile Veissier, Adrien Nicolas
SYTL 2.1	Fri	14:30–15:00	C/gHS	**Electron vortex beams: Twisted matter waves** — •Peter Schattschneider
SYTL 2.2	Fri	15:00–15:30	C/gHS	**Inelastic effects on the lateral wave function of electron beams** — •Javier García de Abajo

Sessions

SYTL 1.1–1.5	Fri	11:00–13:00	C/gHS	**Symposium on interactions between twisted light and particles I (SYTL)**
SYTL 2.1–2.5	Fri	14:30–16:30	C/gHS	**Symposium on interactions between twisted light and particles II (SYTL)**
SYTL 3.1–3.4	Thu	17:00–19:00	C/Foyer	**Poster: Twisted light and particles (SYTL)**

SYTL 1: Symposium on interactions between twisted light and particles I (SYTL)

Time: Friday 11:00–13:00 Location: C/gHS

Invited Talk SYTL 1.1 Fri 11:00 C/gHS
Optical curl forces and beyond — •Michael Berry — H H Wills Physics Laboratory, University of Bristol, UK

A physical example of a force that depends on position but is not derivable from a potential, that is, a nonconservative force with non-zero curl, is the force on a dielectric particle in an optical field. The resulting dynamics need not be Hamiltonian or Lagrangian, yet is non-dissipative. Noether's theorem does not apply, so the link between symmetries and conservation laws is broken. The physical existence of curl forces has been controversial and the subject of intense debate among engineers. Motion under curl forces near optical vortices can be understood in detail, and the full series of 'superadiabatic' correction forces derived, leading to an exact slow manifold in which fast (internal) and slow (external) motion of the particle is separated.

Invited Talk SYTL 1.2 Fri 11:30 C/gHS
Quantum memories for twisted photons — •Elisabeth Giacobino, Julien Laurat, Dominik Maxein, Lambert Giner, Lucile Veissier, and Adrien Nicolas — Laboratoire Kastler Brossel, UPMC, ENS, CNRS, Paris, France

For quantum information, critical resources are quantum memories, which enable the storage of quantum data. They will also allow the distribution of entanglement at large distances, in order to overcome transmission losses, since the no-cloning theorem prevents the amplification of a quantum signal. A quantum memory relies on an efficient coupling between light and matter, in order to achieve reversible mapping of quantum photonic information in and out of the material system. In our system this transfer involves electromagnetically induced transparency (EIT) based on three-level transitions in a cold cesium atomic ensemble. With this set-up we have shown efficient storage of pulses carrying orbital angular momentum (OAM) at the single photon level. Laguerre-Gauss LG+1 and LG-1 modes were imprinted on the signal pulse, using a spatial light modulator. Then superpositions of LG modes, i.e. Hermite Gaussian modes were stored and retrieved. A full memory characterization (process tomography) over the Bloch sphere was performed and allowed us to demonstrate quantum fidelity. We thus demonstrated a quantum memory for orbital angular momentum photonic qubits. Single photons carrying OAM are promising for the implementation of qubits and qudits since OAM constitutes a quantized and infinite space. Interfacing them with quantum memories opens the way to their use in quantum networks.

SYTL 1.3 Fri 12:00 C/gHS
Spatially dependent electromagnetically induced transparency — •Neal Radwell[1], Thomas William Clark[1], Bruno Piccirillo[2], Stephen Mark Barnett[1], and Sonja Franke-Arnold[1] — [1]SUPA, School of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, UK — [2]Dipartimento di Fisica, Universita di Napoli *Federico II*, Complesso Universitario di Monte S. Angelo, 80126 Napoli, Italy

Recent years have seen vast progress in the generation and detection of structured light, with potential applications in high capacity optical data storage and continuous variable quantum technologies. Here we measure the transmission of structured light through cold rubidium atoms and observe regions of electromagnetically induced transparency (EIT). We use q-plates to generate a probe beam with azimuthally varying phase and polarisation structure, and its right and left circular polarisation components provide the probe and control of an EIT transition. We observe an azimuthal modulation of the absorption profile that is dictated by the phase and polarisation structure of the probe laser. Conventional EIT systems do not exhibit phase sensitivity. We show, however, that a weak transverse magnetic field closes the EIT transitions, thereby generating phase dependent dark states which in turn lead to phase dependent transparency, in agreement with our measurements.

SYTL 1.4 Fri 12:20 C/gHS
Chiral optical force — •Robert P. Cameron and Stephen M. Barnett — School of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ

Light carrying helicity in unusual ways can be employed to accelerate the opposite enantiomers of a chiral molecule in opposite directions; a remarkable phenomenon that may find use in a wealth of new applications.

SYTL 1.5 Fri 12:40 C/gHS
Ionization and excitation of atoms by twisted light — •Andrey Surzhykov — Helmholtz Institute Jena, Fröbelstieg 3, 07743 Jena

Owing to the progress in the production and application of twisted (or vortex) light beams, more possibilities arise to explore the role of of the orbital angular momentum (OAM) in the coupling between radiation and matter. In the past, a number of studies have focused on the orbital momentum transfer to colloidal particles, Bose–Einstein condensates or even semiconductors. More recent studies, moreover, aim to better understand the OAM–effects in *fundamental* light–matter interaction processes such as the photon absorption and scattering by atoms, as well as the atomic photoeffect. In this contributions, therefore, we present a theoretical study of the photo–ionization [1] and excitation [2,3] of many–electron atoms and ions by twisted light. By making use of the density matrix theory we analyze the interaction of vortex beams with macroscopic targets of randomly distributed atoms. We argue that for such a (realistic) scenario the OAM of the incident light may strongly affect both the angular distribution of photo–ionized electrons and the magnetic sublevel population of photo–excited atoms. In order to illustrate the effect of the OAM–transfer, detailed calculations will be presented for the interaction of alkali atoms with twisted light.

[1] O. Mayula *et al.*, J. Phys. B **46**, 205002 (2013).
[2] H. M. Scholz–Marggraf *et al.*, Phys. Rev. A **90**, 013425 (2014).
[3] A. Surzhykov *et al.*, Phys. Rev. A *submitted.*

SYTL 2: Symposium on interactions between twisted light and particles II (SYTL)

Time: Friday 14:30–16:30 Location: C/gHS

Invited Talk SYTL 2.1 Fri 14:30 C/gHS
Electron vortex beams: Twisted matter waves — •Peter Schattschneider — Vienna University of Technology, 1040 Vienna, Austria

After the discovery of vortex electrons in 2010, free electrons with topological charge can now be routinely created in the electron microscope. Such vortices are characterized by a spiralling wavefront and a phase singularity at the center, similar to optical vortices that were described by Nye & Berry in 1974. Owing to their short wavelength, these matter waves can be focused to atomic size. Another novel aspect is their magnetic moment, quantized in multiples of the Bohr magneton, independent of the electron spin. These features make electron vortices extremely attractive as a nanoscale probe for solid state physics.

Although the theory of electron vortices in free space is well understood, interaction with fields or matter is more involved. Experimentally, a non-classical rotation mechanism in magnetic fields was found. It is caused by the Landau-Zeeman phase, analogous to the Berry phase causing rotation of optical beams. Nanocluster manipulation, breaking of rotational symmetry to distinguish enantiomeres, and detection of spin polarisation of single atomic columns was demonstrated. Electron vortices could serve as tweezers to move or rotate single atoms or molecules, or to detect sub-meV energy differences in the electron microscope.

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Invited Talk SYTL 2.2 Fri 15:00 C/gHS
Inelastic effects on the lateral wave function of electron beams

— •Javier García de Abajo — ICFO-The Institute of Photonic Sciences, Mediterranean Technology Park, Av. Carl Friedrich Gauss 3, 08860 Castelldefels (Barcelona), Spain

Electron beams carry spatial information encoded in their lateral wave function, which evolves as the beam interacts with different parts of a microscope, as well as with a sample. In this talk, we will formulate a rigorous theoretical analysis for the evolution of an electron beam due to inelastic interaction with some of those elements. In particular, we will study the transfer of orbital angular momentum between vortex electron beams and chiral samples, such as staircase plasmonic nanostructures and biomolecules, which are predicted to produce large dichroism in the momentum-resolved electron energy-loss spectra. Additionally, we will discuss the effect of thermal noise during the electron interaction with distant materials, for example when the electron is moving along the center of a hollow metallic tube, or when it is divided by a biprism, passed above a surface, and later recorded in the far field. Recently observed stochastic thermal deflections and lost of visibility in the interference fringes are shown to be explained by this formalism in semi-analytical form.

SYTL 2.3 Fri 15:30 C/gHS

Electron-spin dynamics in elliptically polarized light — •Heiko Bauke[1], Sven Ahrens[1], Rainer Grobe[2], and Christoph H. Keitel[1] — [1]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg — [2]Intense Laser Physics Theory Unit and Department of Physics, Illinois State University, Normal, Illinois 61790–4560 USA

Electrons as well as elliptically polarized light carry spin angular momentum. Although it is well-known that different angular momentum degrees of freedom may couple to each other, the coupling of electronic and photonic spin degrees of freedom has been considered rarely. We demonstrate that the photonic spin density can induce electron-spin precession [1, 2]. This effect is of similar origin as the well-known spin-orbit coupling. The spin-precession frequency is proportional to the product of the laser field's intensity and its spin density. The electron-spin dynamics is analyzed by employing exact numerical methods as well as time-dependent perturbation theory based on the fully relativistic Dirac equation and on the nonrelativistic Pauli equation that is amended by a relativistic correction that accounts for the light's spin density. Although, the predicted spin precession is an intrinsic relativistic effect it may be observed also at nonrelativistic laser intensities.

[1] H. Bauke, S. Ahrens, C. H. Keitel, R. Grobe, *New Journal of Physics*, **16**, 103028 (2014)
[2] H. Bauke, S. Ahrens, R. Grobe, *Phys. Rev. A*, **90**, 052101 (2014)

SYTL 2.4 Fri 15:50 C/gHS

Design and realisation of variable C shaped structured illumination — •Michael Mousley, Jun Yuan, Mohamed Babiker, and Gnanavel Thirunavukkarasu — University of York, UK

Computer generated holograms (CGHs) have been designed to create structured illumination with a C shape. The structured illumination is based on a vortex state, however the inclusion of radial phase gradients leads to non integer topological charge and a redistribution of intensity in the far field diffraction pattern. By analysing the phase gradients present in the wavefunction the structured illumination pattern can be predicted and independent control of the radius and opening angle is possible. C shaped illumination is experimentally produced in an electron microscope showing two different opening angles , using two different CGH mask types. C-shaped structured illumination offers interesting particle interactions and trapping possibilities with the ability to control the size of the gap between trapped particles at the ends of the intensity curve. C shaped illumination promises potential applications both in the optical and electron beam lithography of metamaterials which utilise split ring structures and dimensions as small as nanometres can be achieved in the electron beam case.

SYTL 2.5 Fri 16:10 C/gHS

Neutron vortex beams and their interaction with laser pulses — •Armen Hayrapetyan and Jörg Götte — Max-Planck-Institut für Physik komplexer Systeme, Nöthnitzer Straße 38, 01187 Dresden

Vortex beams are known to carry quantized orbital angular momentum along their axes of propagation, they possess phase singularities occurring at the center where the beam intensity is zero. While recent advances in technology have lead to creation of both optical and electron vortex beams, called also twisted light and electrons, there have been striking yet largely unexplored studies on other types of material vortex beams. To deepen this analogy between the light and matter waves, we report on the first study of neutron vortex beams (NVBs) and their interaction with plane-wave laser pulses within the framework of relativistic Dirac theory. The interaction with the field is determined via the anomalous magnetic moment of neutron that manifests itself in the exact, Skobelev solutions of the Dirac equation, analogous to the Volkov states of relativistic electrons. To characterize a twisted state of laser-driven neutrons, we construct analytically exact solutions of the Dirac equation that demonstrate the spin-to-orbit conversion for the NVB and the influence of light upon it. Our new solutions generalize, on the one hand, the recently obtained vortex-beam solutions of the field-free Dirac particles, on the other hand, the Dirac-Skobelev solutions for the laser-driven plane-wave neutrons. We pay a particular attention to the evolution of twisted neutrons in the presence of high-power laser fields that have become accessible during the last decade.

SYTL 3: Poster: Twisted light and particles (SYTL)

Time: Thursday 17:00–19:00 Location: C/Foyer

SYTL 3.1 Thu 17:00 C/Foyer

Photoionization of the hydrogen molecular ion by twisted light — •Anton Peshkov[1], Stephan Fritzsche[1,2], and Andrey Surzhykov[1] — [1]Helmholtz-Institut Jena, Germany — [2]Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena, Germany

During the last decades the photoionization of diatomic molecules has been studied intensively in both experiment and theory. In these studies special attention has been paid to the interference between electrons emitted from either of two atomic centers of molecule. This interference leads to the oscillatory behavior of the angular-differential cross section similar to what was observed in the Young's double-slit experiment. Up to the present the Young-type ionization studies have been performed mainly with a plane wave incident radiation. However, owing to the recent developments in optics the photoionization of diatomic molecules can be explored also by using the twisted light beams. These beams are designed to carry a non-zero projection of the orbital angular momentum (OAM) onto to their propagation direction and can be produced with energies up to 100 eV. In this contribution we have investigated the interaction of aligned molecules with twisted Bessel light. Analysis is performed within the nonrelativistic framework and the first Born approximation. Detailed calculations have been performed for the hydrogen molecular ion H_2^+, whose electronic wave function was constructed as a linear combination of atomic orbitals. Results of these calculations indicate that the angular-differential cross section is sensitive to the position of the molecule within the wave-front as well as to the OAM and polarization of incident radiation.

SYTL 3.2 Thu 17:00 C/Foyer

Photoabsorption and ionization of twisted light by many-electron atoms and ions — •Stephan Fritzsche[1,2], Daniel Seipt[1], Valery Serbo[3], and Andrey Surzhykov[1] — [1]Helmholtz-Institut Jena, 07743 Jena, Germany — [2]Theoretisch-Physikalisches Institut, Universität Jena, 07743 Jena, Germany — [3]Novosibirsk State University, 630090 Novosibirsk, Russia

The excitation of many-electron atoms and ions by twisted light has been investigated within the framework of the density matrix theory and Dirac's relativistic equation. In particular, general expressions were derived for the alignment of the excited states if the incident photons are prepared in a coherent superposition of two twisted Bessel beams. It is shown that both, the population of the excited atoms as well as the angular distribution of the photoelectrons, are sensitive to the transverse momentum and the (projection of the) total angular momentum of the incident radiation [1].

[1] A. Surzhykov *et al.*, submitted (2014).

SYTL 3.3 Thu 17:00 C/Foyer

A basis of states for vortex beams — •Koen van Kruining — Max Planck Institut für Physik komplexer Systeme, Dresden

Quantum mechanics requires one to decompose a physical system in a complete orthonormal basis of eigenstates. For twisted light, a basis of transverse electric and transverse magnetic beams is presented. This basis is then applied for identifying the spin eigenstates and describing the interaction of a vortex beam with a birefringent medium.

SYTL 3.4 Thu 17:00 C/Foyer

Relativistic electron beams carrying orbital angular momentum — •Teuntje Tijssen and Mark Dennis — H. H. Wills Physics Laboratory, Bristol, United Kingdom

A simple analytic form of a relativistic electron beam carrying orbital angular momentum is the so-called Bessel beam solution of the Dirac equation, whose components are eigenfunctions of the angular momentum operator around the beam axis with different integer azimuthal labels. Close to the axis of the beam, the different angular momentum labels of different components give rise to an angular interference effect, somewhat similar to the quantum cores studied for optical vortices. our analytic investigation includes careful regularisation of the relativistic electron Bessel beams to have finite energy and self-consistency with the induced electromagnetic field along the core.