Research Potential of the Twisted Photon Beams

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Objectives

- Discuss the properties of of photon beams that carry large angular momentum ($>\hbar$)

  - Generation
  - Applications
  - Compton backscattering

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Introduction

- Photons carry linear momentum $p=\hbar k$ (k=wave vector)
- Photons carry both spin angular momentum (SAM) and orbital angular angular momentum (OAM) – may be separated in paraxial approximation
  - Circularly polarized plane-wave photons carry $J_z=\pm\hbar$ along the propagation direction z *(Beth's experiment, 1936)*
  - Spherical waves: expansion in terms of angular momentum eigenfunctions, position dependence of vector potential $A_\mu(x)$ contains OAM information
  - Beams of light with azimuthal beam dependence *exp(ilϕ) (*e.g, Laguerre-Gaussian modes*) can carry large values of OAM (*Allen et al, 1992*).

Review: Yao, Padgett, *Advances in Optics and Photonics* **3**, 161–204 (2011) and references therein

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Orbital vs Spin Angular Momentum *(from Yao'11 review)*
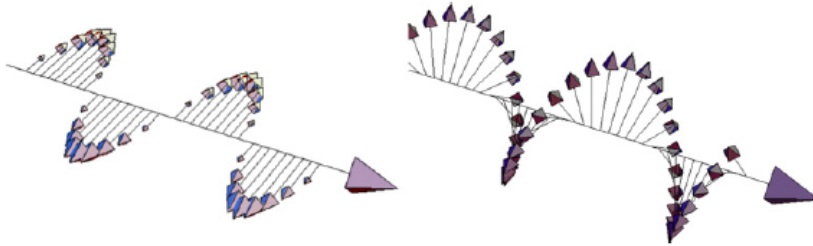
The spin angular momentum (SAM) of light is connected to the polarization of the electric field. Light with linear polarization (left) carries no SAM, whereas right or left circularly polarized light (right) carries a SAM of $\pm\hbar$ per photon.
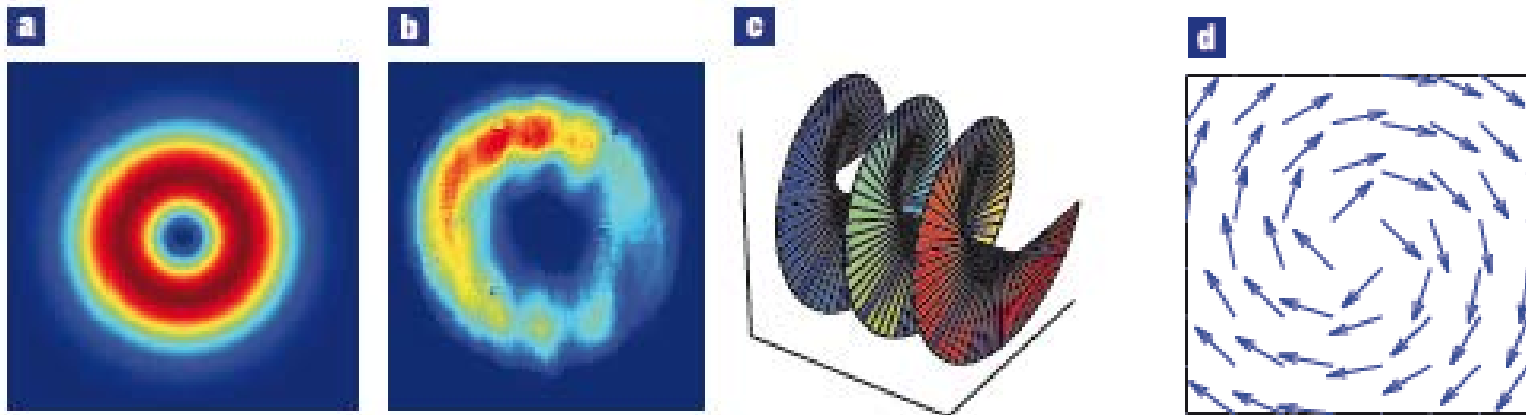

(a)　(b)

(c)　(d)
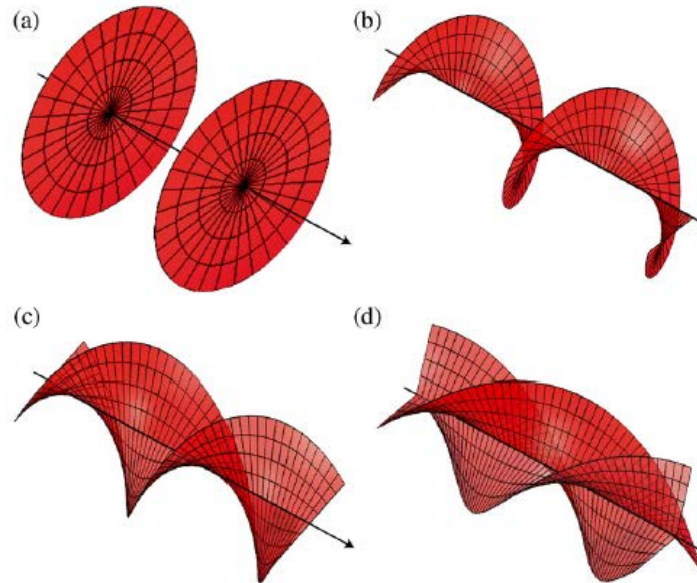
Helical phase fronts for (a) $\ell = 0$, (b) $\ell = 1$, (c) $\ell = 2$, and (d) $\ell = 3$.

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Twisted Photons

- Quantization of light beams having azimuthal phase dependence *exp(ilφ)* lead to a concept of *twisted photons*

G.Molina-Terriza, J.Torres, L. Torner, "Twisted Photons", *Nature Physics,* May 2007.

The typical transverse intensity pattern of a light beam with orbital angular momentum, (a) theory (b) experiment. The light beam exhibits a dark spot in the center, and a ring-like intensity profile. (c) Azimuthal dependence of beam phase results in a helical wavefront.

(d) Orientation of the local momentum of the beam has a vortex pattern (hence another name, *an optical vortex*).

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Transverse Beam Profile

. OAM light beam is characterized with a special transverse profile (example from AA, Carlson, Mukherjee, in preparation)

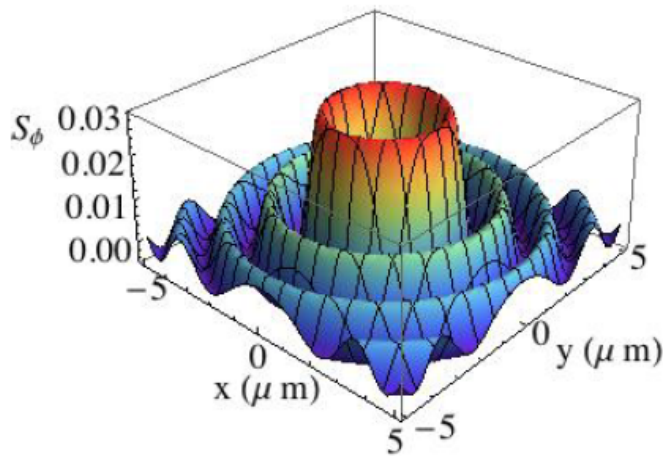. Intensity dip on the beam axis, with transverse size > wavelength

FIG. 1: The size of Poynting vector azimuthal component as a function of position in the transverse plane. For this illustration, the photon wavelength is 0.5 microns, the pitch angle is 0.2 radians, and $m = 4$.
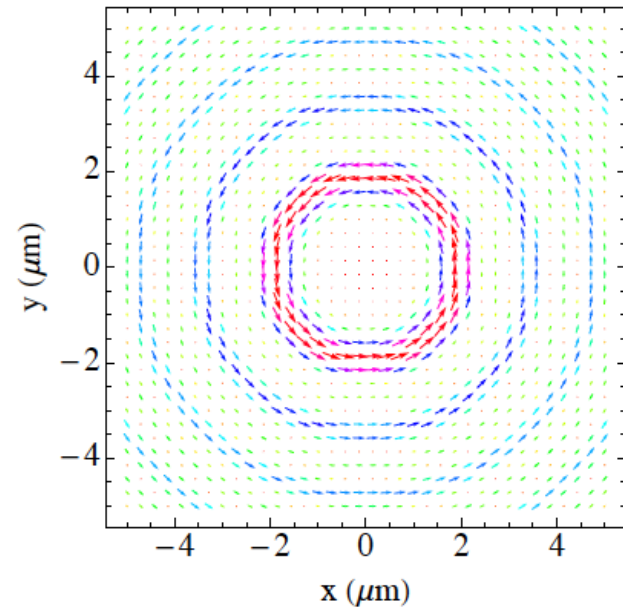

FIG. 2: A plot of $2\pi\rho$ times $\vec{S}$ projected onto the transverse plane. One sees the major bands of $\vec{S}$ circulating in the same direction, building up the large orbital angular momentum. Also for this illustration, $\lambda = 0.5\mu m$, $\theta_k = 0.2$ radians, and $m = 4$.

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Generation of Light Beams with Orbital Angular Momentum

- A diffraction grating with fork dislocation centered on the beam axis, could convert the fundamental Gaussian mode from any laser into a helically phased mode [V. Bazhenov, M. V. Vasnetsov, and M. S. Soskin, "*Laser-beams with screw dislocations in their wave-fronts*," JETP. Lett. 52, 429–431 (1990).] Commonly accepted method for producing helically phased beams.

- Spiral Phase Plates: Gaussian beam is passed through optical media, with azimuthal dependence in thickness
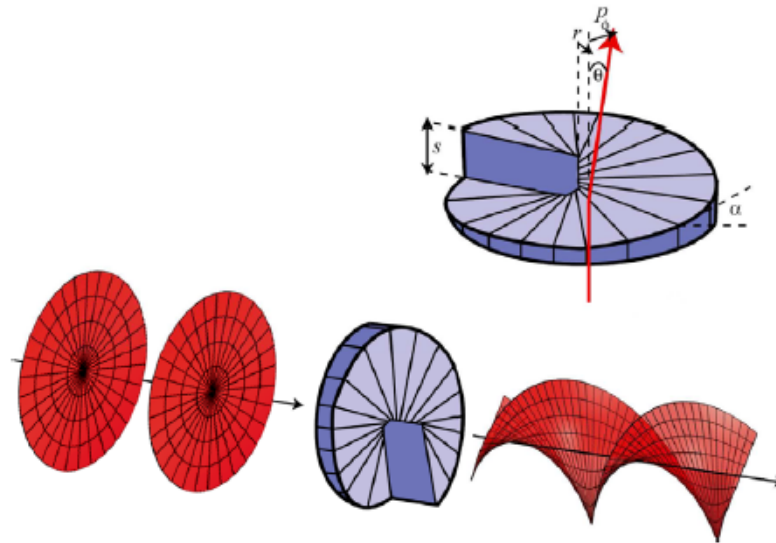
A spiral phase plate can generate a helically phased beam from a Gaussian. In this case $\ell = 0 \rightarrow \ell = 2$.

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Generation of OAM Beams with Helical Undulators

- Recent paper from Rosenzweig's group (UCLA):

E. Hemsing, A. Marinelli, and J. B. Rosenzweig, *"Generating Optical Orbital Angular Momentum in a High-Gain Free-Electron Laser at the First Harmonic,"* Phys. Rev. Lett. 106, 164803 (2011).

- AA, Mikhailichenko, On Generation of Photons Carrying Orbital Angular Momentum in the Helical Undulator, E-print: arXiv 1109.1603

  - Considered properties of synchrotron radiation by charged particles passing through a helical undulator. Shown that all harmonics higher than the first one radiated in a helical undulator carry OAM. Large K-factors favor large values of OAM for generated radiation.

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Helical Undulators (cont)

- AA, Mikhailichenko, On Generation of Photons Carrying Orbital Angular Momentum in the Helical Undulator, E-print: arXiv 1109.1603
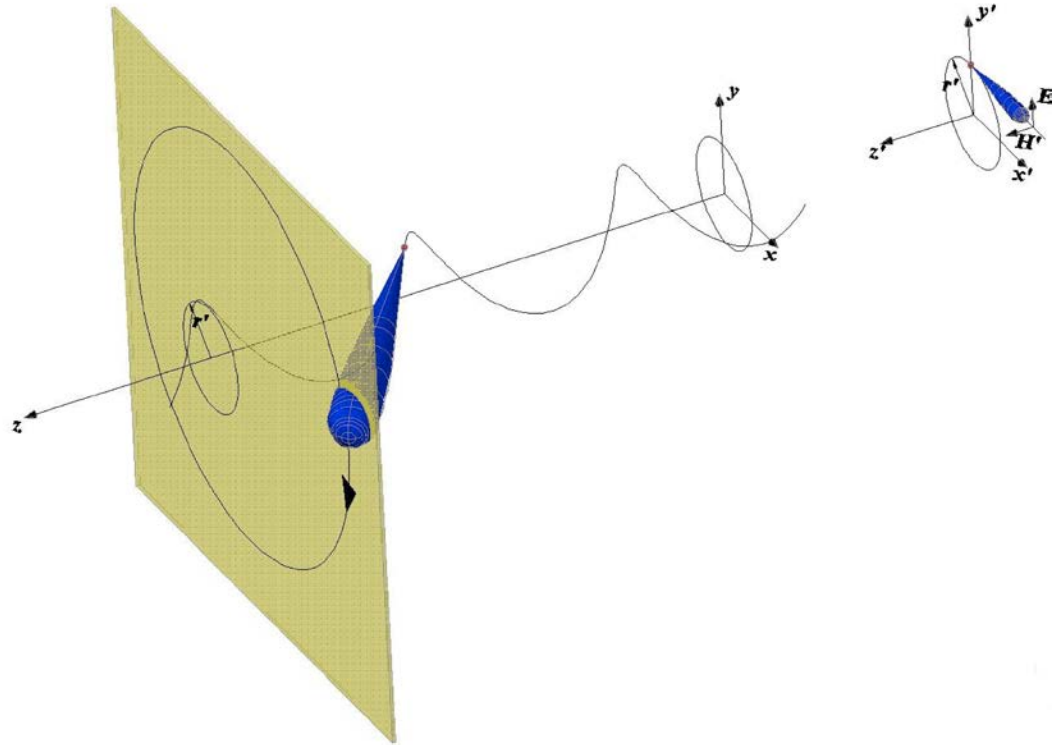

Figure 1. In a moving frame, the radiation has an electron as a point source moving along the circle with the radius $r' = \lambda_u K / \gamma$. In the Lab frame the cone of radiation is tilted toward the direction of motion (z-axis) by the angle $1/\gamma$, so the projector-type radiation is emitted from the off-axis location.

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Transfer of Angular Momentum

- For optical wavelengths, transfer of Orbital AM differs from Spin AM.
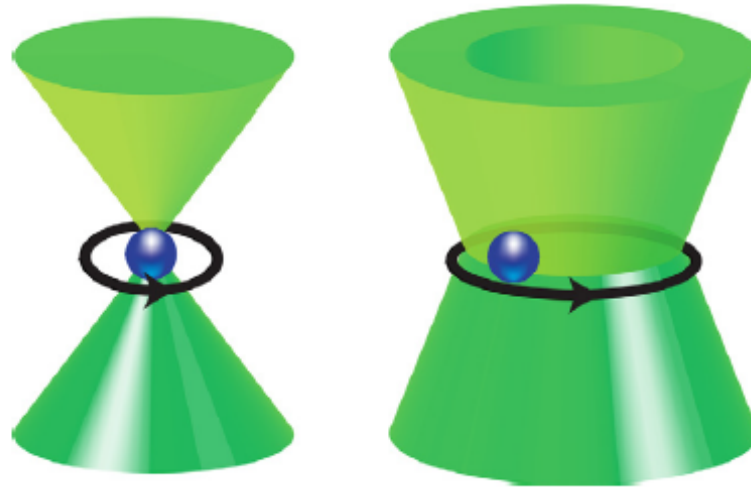
Transfer of angular momentum in optical tweezers. A trapped object can be rotated either by the transfer of SAM from a circularly polarized beam (left) or by the transfer of OAM from a high-order Laguerre–Gaussian beam.

- Important: wavelength vs the target size

  - Wavelength >> target size: OAM transfer results in linear momentum of the target as a whole

  - Wavelength < target size: OAM results in target rotation

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Absorption of Twisted Photons

- Translation or rotation?

    - Mechanism depends on the dimensions of target vs wavefront cross section *S*

    - Depending on a topological number, wavefront cross section may be from a few to a few hundred wavelength

    - If the target size is of the order *S* or less, an essential fraction of photon energy is transferred to *rotation* of the target.

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Atomic Excitations with High-l Photons

- Twisted photons may enhance atomic transitions with large transfer of angular momentum (Picon et al, 2010; AA, Carlson, Mukherjee, in preparation).

  - <u>Showstopper</u>: an atom must be close to the beam axis, but there is a dip in intensity there! Result: the probability is suppressed, typical cross sections are picobarns).

  - <u>Reason</u>: wavelength >> atomic size, atomic transitions are caused by long-wavelength photons

  - Situation will change in hadronic physics: need photons with wavelength < fm to excite a nucleon.

Twisted X-rays

- May be generated directly in twisted undulators by energetic electrons
- Or via Compton backscattering of less energetic electrons
  - Implications: provide an additional degree of freedom in absorption of nano-scale particle, absorption will be a function of topological number for the same wavelength

Twisted Photons for Hadrons vs Atoms

- For most of atomic transitions (excluding Rydberg states), the atom samples a small fraction of transverse beam profile => OAM is not transferred to internal degrees of freedom, but results in linear momentum of the entire atom

- For excitation of a baryon with a twisted photon, $\gamma_T N \to N^*$ OAM will be passed to internal degrees of freedom and will help to get insight into nucleon structure

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How to Generate Twisted Photons in MeV-GeV?

- Serbo et al proposal (2010): Compton backscattering.

U.D. Jentschura V.G. Serbo

Generation of High-Energy Photons with Large Orbital Angular Momentum by Compton Backscattering.

Phys.Rev.Lett. 103 (2011) 013001, e-Print: arXiv:1008.4788;

Compton Upconversion of Twisted Photons: Backscattering of Particles with Non-Planar Wave Functions. Eur.Phys.J. C71 (2011) 1571, arXiv:1101.1206.

- Theoretically demonstrated that OAM properties of twisted photons are preserved in Compton backscattering.
- If holds, it provides a new tool in nuclear, hadronic and high-energy physics, that are photon beams with pre-selected OAM along their direction of propagation.

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Summary

- Twisted photons carry large orbital angular momenta

- If coherence conditions are satisfied, absorption of twisted photons excited rotational degrees of freedom in the targets

- Can be applied at widely different scales, from dust particles, to nanoparticles, molecules, (Rydberg) atoms, and nuclei

- Accelerator-based light source are most efficient for generating twisted X-rays and gamma-rays

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