A Vortex Electron Source for Nuclear Physics

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Outline

• What are vortex beams and how are they produced.
  - Photons
  - Electrons

• Applications of vortex beams.
  - Nuclear physics with vortex beams

• R&D projects to develop accelerated vortex electron beams at JLab.
  - Source and detector

• Summary
Photons carry linear momentum and angular momentum.

Kepler suggested that comet tails always point away from the Sun because light carries linear momentum.

Einstein showed that linear momentum of a photon is $\hbar k$.

In 1909 Poynting showed that light has angular momentum associated with circular polarization. For single photon $L=\pm\hbar$.

Spin angular momentum (SAM)
- circular polarization
- $\sigma\hbar$ per photon
Photons also carry angular momentum independent of polarization.

In 1992 L. Allen et al. showed that light beams with azimuthal phase dependence of $\exp(-i\ell \phi)$ carries angular momentum independent of polarization. For single photon $L=\ell \hbar$

$L. \text{ Allen et al.}, \text{ Phys. Rev. A}45, \text{ 8185 (1992)}$

Images from M. Padgett et al., Physics Today, May 2004, p35
Photons carry real orbital angular momentum.

Orbital angular momentum (OAM) from helical phase fronts

\[ \ell = \text{topological (vortex) charge} \]
\[ \ell = 0 \text{ (plane wave)} \]
\[ \ell = 1 \text{ (helical wave)} \]
\[ \ell = 2 \text{ (double helical wave)} \]
\[ \ell = 3 \text{ (pasta, fusilli wave)} \]

Images from M. Padgett et al., Physics Today, May 2004, p35
Orbital angular momentum carried by photons has been experimentally demonstrated.

with holograms of dislocations & fork gratings

and with diffraction gratings with spiral phase
(thickness varies with azimuthal angle)

Difference between SAM and OAM in photons demonstrated with optical tweezers.

video frames of particles trapped at the focus of a vortex beam with:

\[ \ell = 8 \text{ and } \sigma = 1 \]

SAM is transferred where the photon is absorbed and the particle spins around their own axis
(with rot. rate \( \Omega_{\text{spin}} \sim 1/\rho \)).

OAM transfer causes the particle to orbit around the beam axis
(with rot. rate \( \Omega_{\text{orbit}} \sim 1/\rho^3 \) as predicted by models of vortex beams).


D. Dutta  Spin 2016, Sept 28 7 / 25
Electrons can have vortex beams too.

300 keV electrons ($\lambda = 2$ pm)

nano-fabed diffractive halograms

plane wave

39 µrad diffraction angle

TEM image

helical phase measured using electron interferometry

B. J. McMorran et al., Science 331, 192 (2011)
Electron vortex beams imply orbital motion of unbound massive charged particle in free space.

Not a helical trajectory, but wave function with helical shape. Orbital motion does not require closed trajectories (in electron’s frame).

A vortex beam is a superposition of straight line trajectories.
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Free electrons with OAM can be modeled as

- helical wave function
- semi classical trajectories

Courtesy of B. J. McMorran
Vortex beams - what are they good for?

Higher resolution imaging
(spiral interferometry)

Novel microscopy
(STEM/EELS with vortex probe)

Terabit communication
(OAM multiplexing)

Nano fabrication

Quantum optics

B. J. McMorran et al.
Wang et al. Nature Photon 2012
Mair et al. Nature 2001
Can we do nuclear physics with vortex beams?

Polarized deep inelastic scattering (DIS): ~30% of the protons’s spin is due to quarks spins

Quest for the remaining ~70% is a major enterprise in NP

- quark OAM
- gluon spin
- gluon OAM

Significant effort underway: both theoretical (GPDs, TMDs) & experimental (JLab, RHIC, CERN, & proposed EIC)
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It is high time we explore new tools such as OAM/vortex beams (electrons).

Photon vortex beams in next talk (Y. Taira).

Leader & Lorcé: the formalism of spin+OAM for photons, applies to quarks and gluons too.

The OAM in vortex electrons is carried by the entire wave.

\[ \mathbf{l} = 1 \text{ vortex electron incident on target (atom, nucleus, \ldots)} \]

target “sees” a slightly tilted plane wave and receives a small kick in the direction of the tilt.

but

unlike photons, the electron OAM has a magnetic moment \( \mu_z = g\mu_B l \)

that can couple to external fields


Can focused electron vortex beams induce angular momentum dependent changes in scattering processes?
Open questions on the way to DIS with vortex electron beams.

- Can we build accelerator ready vortex electron sources?
- Are there scattering observables that can be used to monitor OAM (twistedness)?
- What opening angles ($P_\perp/P_z$) are appropriate for scattering with vortex beams?
- Will the vortex beams retain their OAM after acceleration?
- Are there spin-orbit correlations that can be useful observables?

R&D activities have been initiated at JLab to help address some of these questions.
First we need a source of vortex electrons.

Existing vortex electron sources are high brightness field emission sources (electron microscope sources)

![Diagram of vortex electron source with a phase plate, objective lens, biprism, screen, and interference pattern.]

or

![Diagram of vortex electron source with a plane wave, diffractive halograms, and interference pattern.]

typical energy
100 - 300 keV
First we need a source of vortex electrons.

Accelerators sources are typically photoemission or thermionic emission electrons generated when laser pulses are incident on a GaAs photocathode. Photoemission sources have lower brightness (higher emittance), not ideal as vortex sources.

From C. Hernandez-Garcia
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Explore field emission from GaAs tips for high brightness photoguns


&

R&D on cryo-cooled photocathodes for low emittance dc high voltage photogun

J. Grames, JLab
We also need scattering observables to monitor vortex electrons.

In existing vortex electron sources OAM is verified by interference or microscopy.

For accelerator based sources we cannot use interference or microscopy.

**Mott scattering may help distinguish between plane wave and twisted wave.**

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We propose to study Mott scattering using an electron microscope source.

Modify/cannibalize existing SEM/TEM sources at the U. of Oregon to build a vortex electron source with fork gratings.

B. McMorrnan’s group at UO

Couple source to spare Mott polarimeter chamber from JLab

Measurements to be performed at U. of Oregon
We also propose to study Mott scattering using a new cryo-cooled low emittance photogun at JLab.
A Mott scattering simulation for vortex electrons has also been built.

The formalism of V. Serbo et al. was used in the simulation.


The vortex electrons beam is approximated as a Bessel beam.

\[ \psi(\rho, \phi, z) = \sqrt{\frac{\lambda}{2\pi}} e^{i p_2 z} \sum_{\sigma} \int \frac{d^2 \lambda}{(2\pi)^2} \left( \frac{\lambda}{\sin(\theta_p)} \right)^{1/2} J_{m-\sigma}(\lambda) U^{(\sigma)}(\epsilon, \lambda) \]

\( p_2 \) - long. momentum, \( \epsilon \) - energy, \( \lambda \) - helicity, 
\( \sigma \) - spin, \( \theta_p \) - opening angle, \( m \) - total ang. momentum

Based on the source at U. of Oregon:
- a realistic beam emittance/brightness is included
- opening angle is simulated over a range of 12 - 50 mrad

Finally the vortex electron beam will be accelerated to 1 - 5 MeV and measured in the Mott polarimeter.

If successful the high brightness source can be inserted in the CEBAF injector or at the Upgrade Injector Test Facility (UITF)

The OAM can be measured in the 5 MeV Mott after acceleration.

J. Grames, JLab
Summary

• Both photons and electrons can carry OAM.

• Focused beams of vortex electrons can be produced using fork gratings or phase plates.

• It is highly desirable to have new tools to probe the spin and OAM structure of nucleons.

• Vortex electrons maybe just the new tool we need.

• A new R&D program is being initiated at JLab to explore how to build vortex electron sources for accelerators and how to measure the OAM of such beams.