非線形逆トムソソン散乱によるガンマ線渦の発生

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Optical vortices forming helical wavefronts

Topological charge

$\ell = 0$

$E \propto \exp(i\ell \phi)$  
Carrying $\ell \hbar$ orbital angular momentum (OAM)

Representative optical vortex: Laguerre Gaussian mode
Poynting vector and total AM

Poynting vector of Laguerre Gaussian mode

\[ S = E \times B \propto \left( \frac{\rho z}{z^2 + z_R^2} e_\rho + \frac{\ell}{k \rho} e_\phi + e_z \right) \]

- \( k \): wave number of LG light
- \( \rho \): distance from the z-axis

spread of the beam

Spiral Poynting vector gives OAM

Total angular momentum

Spin AM + OAM = ± ħ + ℓ ħ or ℓ ħ

Circularly polarized optical vortex
Linearily polarized optical vortex

Transfer of OAM using optical vortex lasers

To a micro particle

To a valence electron

Quadruple transition at 729 nm of $^{40}$Ca$^+$ ion.

$\Delta m = -2$


Generation of gamma-ray vortices (more than sub-MeV energy) and development of their application.

Developed vortex beams

- Micro/THz wave
- Laser
- UV
- X-ray

Except for the electromagnetic wave

- 300 kV electron
- Cold neutron

Unexplored region

Gamma-ray vortex
Applications of gamma-ray vortices

Compton scattering


Cross section ($E_0 = 500$ keV)

$\theta_p$: Momentum ratio between transverse and longitudinal component

They may be applied to solid state physics by being expanded to magnetic Compton scattering.

Insight into the proton structure

Proton spin puzzle: Only 30% of the proton spin is carried by the quark spin.

If OAM of gamma-rays affects to OAM of quark or gluon, it becomes novel probe of the proton spin.

Other potential application

Excitation of nucleus, Generation of positron vortices, Astrophysics, etc.
Generation of optical vortices

Cylindrical lens

Spiral phase plate

Fork grating

Plane wave

Charge, m = 4

OAM = m × n

Optical vortices from free electrons

An electron moving on a circular trajectory emits optical vortices

Electron

Electric field emitted by a helical undulator

\[ E \propto C \exp \left\{ i (n-1) \phi \right\} e^+ \]

nth higher harmonics carry \((n-1)\hbar\) OAM

This was demonstrated in ultraviolet and soft X-ray regions.

2nd harmonics
(1\(\hbar\) OAM) → 1 spiral interference fringe
(Helical + Spherical)

J. Bahrdt et al., PRL 111 034801 (2013).
Gamma-ray vortices via NITS

Nonlinear inverse Thomson scattering (NITS)

Electron trajectory inside a laser

Gamma-ray vortex

Circularly polarized laser

\( a_0 \): Laser strength parameter
\( \gamma_0 \): Lorentz factor of an electron
\( E_L \): Energy of laser photon
\( 10^{18} \text{ W/cm}^2 \) reaches \( a_0 \approx 1 \)

\[
E_\gamma = \frac{4n\gamma_0^2 E_L}{1 + a_0^2/2}
\]

Spatial distributions of NITS gamma-rays

Only higher harmonic gamma-rays show annular intensity distribution, which is consistent with the characteristics of an optical vortex.

NITS using RF accelerated electrons

**SLAC**
C. Bula et al., PRL 76 3116 (1996).

**BNL**
M. Babzien et al., PRL 96 054802 (2006).

Spatial distributions of linearly polarized X-rays

with 0.01 mm Ag foil
NITS using laser wakefield accelerated e-

Ludwig-Maximilians-Universität München


AIST

E. Miura et al., APEX 7 046701 (2014).

U of Nebraska-Lincoln


Rutherford Appleton Laboratory

G. Sarri et al., PRL 113 224801 (2014).
Second harmonic X-rays at BNL ($a_0=0.6$)

Electron

$\gamma = 128$

$\lambda_0 = 10.6 \, \mu m$, pulse energy = 2 J,
$2\omega_0 = 100 \, \mu m$, pulse width = 5 ps (FWHM)

Calculation (Y. Taira)

Measurement (BNL)

This will be a X-ray vortex.

E = 13 keV ($\lambda = 0.095$ nm)

Next step

Measurement of a herical wavefront.

Y. Sakai et al., PRSTAB 18 060702 (2015).
Experimental plans at KPSI and UVSOR-III

**KPSI of QST**

Microtron + J-KAREN-P PW laser (800 nm)

\[ \gamma_0 = 300 \quad a_0 < 3 \]

0.4 MeV gamma-ray vortices.

\[ N_\gamma \approx 10^3 \sim 10^5 \text{ photons/sec} \]

Purpose:
Measurement of annular distribution and helical wavefront.
Study of Compton scattering.

**UVSOR-III**

90-degree collision

\[ \gamma_0 = 1470 \quad a_0 \sim 0.6 \]

10 MeV gamma-ray vortices.

\[ N_\gamma \sim 800 \text{ photons/sec} \]

Purpose:
Measurement of annular distribution.
Study of Compton scattering and nuclear excitation.
Measurement of $\gamma$-ray vortex is challenging

Explore measurement methods of $\gamma$-ray vortices
Diffraction method

Triangle aperture

Circularly polarized laser

Electron

Magnet

Triangle aperture

20 µm

Imaging detector

X-ray vortex

Diffracted X-ray

Calculated diffraction pattern (5keV)

2\textsuperscript{nd} harmonics

3\textsuperscript{rd} harmonics

A triangle aperture can be used to measure the helical wavefronts.

R&D is carried out at SPring-8.
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Summary

- Gamma-ray vortices can be generated by nonlinear inverse Thomson scattering.
  
  \[ \text{n-th higher harmonic gamma-rays carry } (n-1)\hbar \text{ OAM.} \]

- Measurement of gamma-ray vortices is a big issue.
  
  In the low energy region, diffraction and interference methods must work.
  
  Compton scattering may work around MeV energy region.

Thank you for your attention!