Feasibility study for measurement of X-ray vortices at ATF

Yoshitaka Taira\textsuperscript{1}, Yusuke Sakai\textsuperscript{2}

\textsuperscript{1}: National Institute of Advanced Industrial Science and Technology (AIST), Japan
\textsuperscript{2}: University of California at Los Angeles
Vortex beams forming helical wavefront

Topological charge

\( \ell = 0 \)

\( \ell = 1 \)

Electric field

\[ E \propto \exp(i\ell \phi) \]

Carrying \( \ell \hbar \) orbital angular momentum (OAM)

Y. Taira, Feasibility study for measurement of X-ray vortices at ATF
Measurement of 9-keV X-ray vortex

- Electron storage ring
- Synchrotron light
- Spiral phase plate (step: 34 µm)
- Metal wire φ7 µm
- X-ray vortex (9 keV)
- Detector

Interference pattern between X-ray vortex and diffracted X-ray from a metal wire

- Fork
- OAM = -1ℏ
- Wire


Y. Taira, Feasibility study for measurement of X-ray vortices at ATF
Vortex beams

Developed vortex beams

Energy (eV)

10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8}

Micro/THz wave  Laser  UV  X-ray

Gamma-ray vortex

Unexplored region

Wavelength

1 m 10 cm 1 cm 1 mm 100 μm 10 μm 1 μm 100 nm 10 nm 1 nm 100 pm 10 pm 1 fm

Exception for the electromagnetic wave

300 kV electron  Cold neutron

Y. Taira, Feasibility study for measurement of X-ray vortices at ATF
Possible applications of gamma-ray vortex

Insight into the proton structure

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

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

quark OAM

gluon spin, OAM

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

Other potential application

Excitation of nucleus
Generation of positron vortices via pair production.
Astrophysics (gamma-ray burst)
Solid state physics (magnetic Compton scattering)

Y. Taira, Feasibility study for measurement of X-ray vortices at ATF
How to generate gamma-ray vortices?

Nonlinear inverse Thomson scattering

Gamma-ray vortex

Electron in helical motion

Circularly polarized laser

Electric field of emitted gamma-rays
\[ \vec{E} \propto C \exp\{i(n-1)\phi\}e_+ \]

nth higher harmonics carry \((n-1)\hbar\) OAM and higher harmonics show annular intensity distribution.


Y. Taira, Feasibility study for measurement of X-ray vortices at ATF
Research objectives

Final goal

We will demonstrate that higher harmonic gamma-rays form helical wavefronts and apply them to nuclear physics.

Problem

The measurement of a helical wavefront in the gamma-ray frequency range is difficult using current technology.

In the 10 keV energy range, diffraction and interference methods can be used to measure the helical wavefronts.

Goal of the first step

We will demonstrate that 2nd harmonic X-rays generated by nonlinear inverse Thomson scattering form a helical wavefront.

Y. Taira, Feasibility study for measurement of X-ray vortices at ATF
Second harmonic X-rays at BNL ($a_0=0.6$)

This result implies that second harmonic X-rays form a helical wavefront.

Y. Taira, Feasibility study for measurement of X-ray vortices at ATF
A triangle aperture can be used to measure the helical wavefronts.

Y. Taira, Feasibility study for measurement of X-ray vortices at ATF
Coherence length and number of photons

Coherence length and angle

\[ L_c = \frac{\lambda R}{2\pi\sigma} \quad \theta_c = \frac{\lambda}{2\pi\sigma} \]

\( \lambda \): wavelength of X-ray
\( R \): distance from source to aperture plane
\( \sigma \): X-ray source size (rms)

When \( \lambda = 0.17 \text{ nm} \), \( R = 2 \text{ m} \), and \( \sigma = 2 \mu\text{m} \), \( L_c = 28 \mu\text{m} \) and \( \theta_c = 14 \mu\text{rad} \).

Coherenence length is larger than a dimension of a triangle aperture.

The number of photons

Electron: \( \gamma_0 = 100 \), charge = 0.16 nC/pulse, pencile beam

Laser: \( \lambda_0 = 9.3 \mu\text{m} \), \( a_0 = 1.0 \), pulse width = 3.5 ps (FWHM)

X-ray: Maximum energy = 7.1 keV (\( \lambda = 0.17 \text{ nm} \))

The number of photons = \( 10^{-3} \sim 10^{-2} \) photons/pulse (\( \theta_c = 14 \mu\text{rad} \))

Single shot measurement is difficult.
Research plan in FY2018

What is important? - Please give us any ideas -

**Small X-ray source size to get large transverse coherence length**

- Is the minimum electron beam size 5 $\mu$m (rms)?
- Is it possible to obtain $< 2 \mu m$ electron source size?
- Can an electron beam size along the one axis be reduced?

- Using short wavelength laser ($\lambda_0 \sim 1 \mu m$)?

**Intense X-ray source to measure at a single or few shots**

- Is a high current electron source available?
- Is $a_0 \sim 1$ laser with the long pulse width possible?

Calculation of other detection methods

- Using a double slit and interference of 1st and 2nd harmonics.

Y. Taira, Feasibility study for measurement of X-ray vortices at ATF
Summary

- Gamma-ray and X-ray vortices are generated by nonlinear inverse Thomson scattering.

- A triangle aperture can be used to measure the helical wavefront.

- However, it is very difficult to achieve the required coherence length of X-rays and the single shot measurement.

- In FY2018, we continue to do theoretical investigation using a double slit and an interference method for a future experiment.

Thank you for your attention!