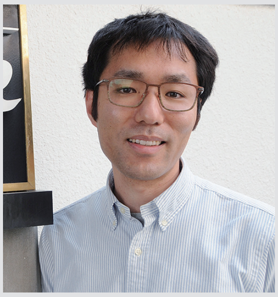
# Development and Utilization of Novel Quantum Beam Sources Using a High Energy Electron Beam

**UVSOR Synchrotron Facility**
**Division of Beam Physics and Diagnostics Research**



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2007 B.S. Nagoya University
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2012 Young Researcher Best Poster Award, 12th International Symposium on Radiation Physics
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Our group develop new electromagnetic wave sources using a high energy electron beam. In the UVSOR-III electron storage ring at the Institute for Molecular Science, a 750-MeV electron beam can be generated. Electromagnetic waves in a wide frequency range from ultraviolet waves to gamma-rays are emitted by interacting the electron beam with magnetic fileds and lasers.

Inverse Thomson (Compton) scattering is a method to generate a high energy gamma-ray by the interaction between a high energy electron and a laser. We have developed ultra-short pulsed gamma-rays with the pulse width of sub-ps to ps range by using 90-degree inverse Thomson scattering (Figure 1). This ultra-short pulsed gamma-rays were applied to gamma-ray-induced positron annihilation pectroscopy (GiPAS). A positron is an excellent probe of atomic scale defects in solids and of free volumes in polymers at the sub-nm to nm scale. GiPAS enables defect analysis of a thick material in a few cm because positrons are generated throughout a bulk material via pair production. Our group is conducting research on improving the properties of the material by using GiPAS.

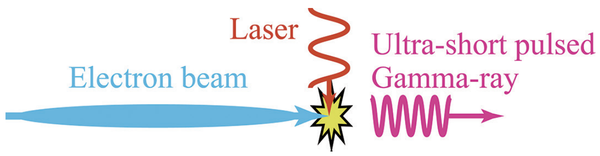


**Figure 1.** Schematic illustration of 90-degree inverse Thomson scattering.

## Selected Publications


- Y. Taira, M. Adachi, H. Zen, T. Tanikawa, N. Yamamoto, M. Hosaka, Y. Takashima, K. Soda and M. Katoh, "Generation of Energy-Tunable and Ultra-Short-Pulse Gamma Ray via Inverse Compton Scattering in an Electron Storage Ring," *Nucl. Instrum. Methods Phys. Res., Sect. A* **652**, 696 (2011).
- Y. Taira, T. Hayakawa and M. Katoh, "Gamma-Ray Vortices from Nonlinear Inverse Thomson Scattering of Circularly Polarized Light," *Sci. Rep.* **7**, 5018 (2017).
- Y. Taira, M. Fujimoto, S. Ri, M. Hosaka and M. Katoh, "Measurement of the Phase Structure of Elliptically Polarized Undulator Radiation," *New J. Phys.* **22**, 093061 (2020).
- Y. Taira, R. Yamamoto, K. Sugita, Y. Okano, T. Hirade, S. Namizaki, T. Ogawa and Y. Adachi, "Development of Gamma-Ray-Induced Positron Age-Momentum Correlation Measurement," *Rev. Sci. Instrum.* **93**, 113304 (2022).
- Y. Taira *et al.*, "Measurement of the Spatial Polarization Distribution of Circularly Polarized Gamma Rays Produced by Inverse Compton Scattering," *Phys. Rev. A* **107**, 063503 (2023).

## 1. Gamma Ray-Induced Positron Annihilation Spectroscopy (GiPAS)

In gamma-ray-induced positron annihilation lifetime spectroscopy (GiPALS), positron lifetime spectrum is calculated by measuring the time difference between a reference signal and a detector output for the annihilation gamma rays, which is emitted when a positron annihilates with an electron inside material. A reference signal is the output of a photodiode located near the injection position of a laser. A $BaF_2$ scintillator and a photomultiplier tube is utilized to detect the annihilation gamma rays. Two detectors are arranged at 180 degrees because two annihilation gamma rays are generated at 180-degree direction.

A digital oscilloscope is used to store the waveforms of the photodiode and the $BaF_2$ detector, and calculate the time difference distribution. One digital oscilloscope for four $BaF_2$ detectors is used as a pair of detection systems. The annihilation gamma rays are generated to whole solid angle. Therefore array detectors are effective to increase the count rate of the annihilation gamma rays and to reduce the measurement time. A detection system with eight detectors and two digital oscilloscopes was constructed (Figure 2). Time resolution is 140 ps in full width at half maximum, which is high despite the use of a 52-mm thick $BaF_2$ scintillator. The count rate is 20 cps.

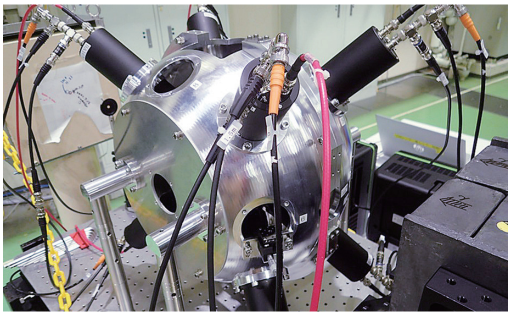

**Figure 2.** Positron annihilation lifetime measurement system using eight detectors and two digital oscilloscope.

User applications are currently underway at BL1U in UVSOR-III, including measurements of bulk materials and in situ measurements of defect formation under stress loading.

Meanwhile, we are also developing gamma-ray-induced spin-polarized positron annihilation spectroscopy using circularly polarized gamma rays. If the electron spins of a sample are ordered in a particular direction and the positrons are also spin-polarized, the Doppler broadening spectra of annihilation gamma rays and the positron lifetime will change. The spin-polarized positrons are generated from the circularly polarized gamma rays inside a sample. From this change, it is possible to obtain information about the electron spins around defects in magnetic materials. To demonstrate the principle of circularly polarized gamma-ray-induced spin-polarized positron annihilation spectroscopy, a pure iron sample is mounted between permanent magnets and the positron lifetime and Doppler broadening are measured.

Inverse Compton scattering of a polarized laser by energetic electrons is an excellent method to generate polarized gamma rays. A 100% polarized laser can generate 100% polarized gamma rays, but polarization varies depending on the scattering angle of the gamma rays. We have experimentally measured the spatial polarization distribution of circularly polarized gamma rays using magnetic Compton scattering that can measure the circular polarization of MeV gamma rays. Measurements of the asymmetry of gamma-ray transmission relative to the magnetized iron at each scattering angle clearly show that gamma rays are circularly polarized near the central axis, and they change from circular to linear polarization as the scattering angle increases.[1)]

## 2. Gamma-Ray Vortices

An optical vortex is an electromagnetic wave with a helical phase structure. When an optical vortex beam is viewed in a plane transverse to the direction of propagation, an annular intensity profile is observed due to the phase singularity at the center axis. An important consequence of the optical vortex is that it carries orbital angular momentum (OAM) due to the helical phase structure.

While fundamental and applied research on optical vortices using visible wavelength lasers is widely studied, much less has been done in ultraviolet, X-rays, and gamma-rays energy ranges. We have proposed for the first time a method to generate a gamma-ray vortex using nonlinear inverse Thomson scattering of a high energy electron and an intense circularly polarized laser. In our method, the circularly polarized laser is important because the helical phase structure arises from the transverse helical motion of the electron inside the circularly polarized laser field. When peak power of a laser achieves terawatt class, high harmonic gamma rays are generated. Only gamma rays more than the first harmonic carry OAM. High harmonic gamma rays show the annular intensity distribution due to this characteristic.

There are few facilities in the world, which can carry out the experiment for the nonlinear inverse Thomson scattering using an intense circularly polarized laser in terawatt class. We carried out the experiment at Kansai Photon Science Institute in Japan, where a 150 MeV microtron and a petawatt laser are available. We were not able to achieve the measurement of an annular intensity distribution of high harmonic gamma rays.

As there is a laser with a pulse energy of 50 mJ and a pulse width of 130 fs (FWHM) in UVSOR-III, the laser strength parameter is 0.4 if the beam size can be focused to 3 µm (rms). Nonlinear inverse Thomson scattering experiments were performed in 2022, but no higher harmonic gamma-ray generation was observed. Concentric fringes were observed in the laser focusing pattern, suggesting that the laser energy was dispersed and the laser strength parameter was reduced. Further improvements will be made and re-experiment is planned in the future.

### Reference

1) Y. Taira *et al.*, *Phys. Rev. A* **107**, 063503 (2023).

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