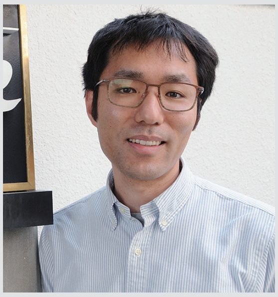
Development and Utilization of Novel Quantum Beam Sources Using a High Energy Electron Beam

UVSOR Synchrotron Facility
Division of Beam Physics and Diagnostics Research



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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.

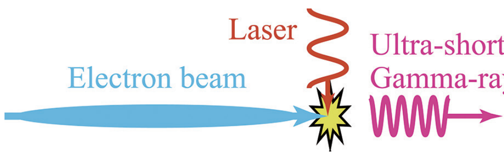

Figure 1. Schematic illustration of 90-degree inverse Thomson scattering.

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, 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).
- Y. Taira, Y. Yang, T. Shizuma and M. Omer, "Generation and Measurement of Gamma Rays with Axially Symmetric Polarization States via Compton Scattering," *Phys. Rev. Res.* **7**, 033130 (2025).

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

In GiPAS, defect analysis is performed by measuring the energy spectrum and emission time distribution (positron lifetime spectrum) of annihilation gamma rays, which are generated when a positron annihilates with an electron inside material. Gamma-ray-induced positron annihilation lifetime spectroscopy (GiPALS) is a technique that measures the time difference distribution between a reference signal and a detector output of annihilation gamma rays. The reference signal is the output of a photodiode placed near the collision point between the electron beam and the laser, which detects the laser just before it generates gamma rays. 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. 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. A typical count rate is 20 cps.

Currently, user applications of GiPALS are underway at BL1U of UVSOR, and users from universities, research institutes, and private companies are using the system. Measurements of samples under special environments such as stress loading, high temperature, gas atmosphere, laser irradiation, hydrogenation, etc., which are difficult to measure with conventional methods using ^{22}Na, are being performed.

Meanwhile, we are also developing gamma-ray-induced spin-polarized positron annihilation spectroscopy using circularly polarized gamma rays. The spin-polarized positrons are generated from the circularly polarized gamma rays inside a sample. 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. 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. We have not been able to measure the difference in positron lifetime due to the helicity inversion of circularly polarized gamma rays, but we will continue research and development.

2. Spatial Polarization Measurement of Gamma-Rays Generated Using Polarized Lasers

Inverse Thomson/Compton scattering of a polarized laser by energetic electrons is an excellent method to generate polarized gamma rays. The development and use of linearly and circularly polarized gamma rays have been conducted. The polarization state of linearly and circularly polarized lasers is homogeneous across their cross sections. However, it is possible to produce lasers with spatially variant polarization states. An example is the axially symmetric polarization state, referred to as an axially symmetric polarized laser or a cylindrical vector beam. Although the polarization characteristics of gamma rays produced by linearly or circularly polarized lasers have been theoretically clarified, that of gamma rays generated by axially symmetric polarized lasers have not. If gamma rays with novel polarization characteristics can be generated, it is possible to develop new ways to use gamma rays.

A novel Compton polarimeter was constructed to measure the linear polarization of MeV gamma rays. Gamma rays are irradiated onto an iron target, and the azimuth distribution of scattered gamma rays is measured by seven NaI detectors to determine the polarization axis of the gamma rays. The gamma rays expand over a diameter of 10 mm. By installing a collimator with a diameter of 1 mm on the gamma ray beam axis and irradiating only the gamma rays that pass through it onto the target, it is possible to measure the polarization axis at that position. Moreover, by scanning the collimator in two dimensions, it is possible to measure the spatial polarization distribution of gamma rays. Figure 2 shows the spatial polarization distribution of inverse Compton scattered gamma rays measured for the first time using the developed polarimeter. We were able to demonstrate that the polarization axis changes depending on the position of the beam cross section in both horizontal and vertical polarization. Gamma rays generated using a circularly polarized laser showed that the outer polarization changed to linear polarization and that the polarization axis was oriented in the azimuth direction. Gamma rays generated using radially and azimuthally polarized lasers were found to possess random polarization near the central axis and azimuth polarization states on the outer region.

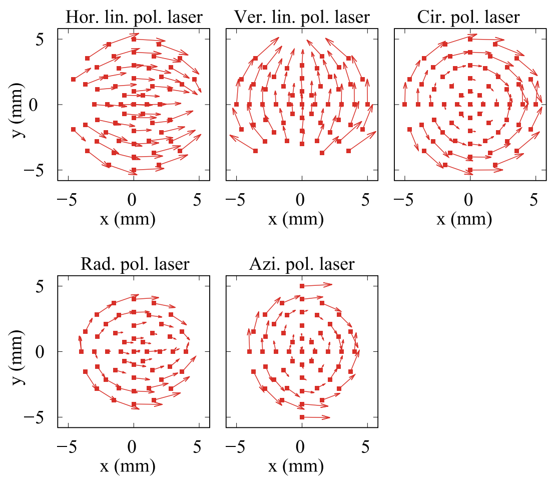

Figure 2. Measured spatial polarization distribution of gamma rays generated using five types of polarized lasers.

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