GENERATION OF 1-MeV QUASI-MONOCHROMATIC GAMMA-RAYS FOR PRECISE MEASUREMENT OF DELBRÜCK SCATTERING BY LASER COMPTON SCATTERING*

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Abstract

The nearly isolated precise measurement of the vacuum contribution, Delbrück scattering, to the elastic scattering of photons off nuclei can be realized by using high-flux linearly-polarized gamma-ray sources. For the proof of principle experiment, an intense linearly polarized gamma-ray beam with an energy lower than 1 MeV should be provided. In order to examine the available gamma-ray performance at the UVSOR facility by colliding a CO_2 laser with a 746-MeV electron beam, a preliminary experiment has been performed. As a result, it was confirmed that the maximum energy of the gamma-rays was slightly lower than 1 MeV and the measured gamma-ray flux was evaluated to be 6×10^{-4} photons/eV/mA/W/s around the peak energy of 950 keV. If we accept a 20 percent energy spread, in case of a 100-W CO_2 laser colliding with a 300 mA electron beam, approximately 4×10^{6}-photons/s gamma-rays could be obtained. This flux is sufficiently high enough for the proof of principle experiment.

INTRODUCTION

Delbrück scattering is the elastic scattering of photons by the electromagnetic field of an atomic nucleus, as a consequence of vacuum polarization [1]. The isolated measurement of Delbrück scattering has not been performed because of interference with other elastic scattering processes. It was recently discovered that, using linearly polarized photons, Delbrück scattering can be measured nearly independently of the other scattering processes [2]. When the gamma-ray energy used for the experiment exceeds the pair creation threshold, 1022 keV, Delbrück scattering by the pair created particles also takes place together with the Delbrück scattering by the vacuum polarization. In order to measure the Delbrück scattering induced by the vacuum polarization, a linearly polarized quasi-monochromatic gamma-ray beam with a maximum photon energy below the pair creation threshold, 1022 keV, should be provided.

Our group considered that the Laser Compton Scattering (LCS) gamma-rays generated in a low energy electron storage ring with a CW CO_2 laser having high averaged power are one good candidate to realize high-flux linearly-polarized gamma-rays below 1022 keV. CO_2 lasers have been used for the generation of LCS X-rays and gamma-rays [3-6] since they can provide high average power or high pulse energy with low photon energy, around 0.117 eV. At the UVSOR facility [7] where a 746-MeV 300-mA electron beam is available, the expected gamma-ray energy is about 1 MeV when a 10.6-µm CO_2 laser is used as the collision laser for a LCS gamma-ray source. In order to check the maximum gamma-ray energy and flux, a preliminary experiment has been carried out.

LASER COMPTON SCATTERING (LCS)

Laser Compton scattering (LCS) is one method to generate a quasi-monochromatic and polarized gamma-ray beam. The schematic diagram of the laser Compton scattering is shown in Fig. 1. A laser photon with an energy of E_p and a relativistic electron with an energy of $E_{e,i}$ collide at the angle of θ_p. As a result, the incident photon is scattered by the relativistic electron and the scattered photon energy is up-converted to E_γ which is expressed as [8]

$$E_\gamma = \frac{E_p(1+\beta\cos\theta_p)}{1-\beta\cos\theta_\gamma+\frac{E_p}{\gamma m_0 c^2}(1-\cos\theta_S)}, \tag{1}$$

where m_0 is the rest mass of the electron, γ is the Lorentz factor, $\gamma = (1-\beta^2)^{-1/2}$, $\beta = v/c$ is the electron velocity relative to the velocity of light c, θ_γ is the angle of the scattered gamma-ray and θ_S is the angle between the incident photon and the scattered gamma-ray. In the case of a high energy

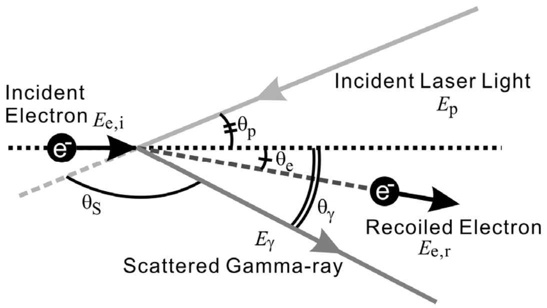

Figure 1: Schematic diagram of the Laser Compton Scattering (LCS).

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* Work supported by the Joint Studies Program (2017) of the Institute for Molecular Science

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ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-MOPML049

electron beam i.e., $\gamma > 1000$, and head-on collision, $\theta_p = 0$, the maximum gamma-ray energy, which can be observed at $\theta_\gamma = 0$, is given as

$$E_\gamma \approx 4E_p\gamma^2 . \qquad (2)$$

The energy of laser photons is up-converted to approximately $4\gamma^2$ times higher energy by the collision with high energy electrons.

LCS Gamma-Rays at UVSOR with CO2 Laser

Several LCS gamma-ray generation experiments have been already conducted at the UVSOR synchrotron radiation facility based on a 750-MeV electron storage ring [9-11]. From the prior experiment using a 1.94-μm fiber laser, the energy of the electron beam circulating in the storage ring has been determined to be 746 ±1 MeV from the maximum energy of the LCS gamma-rays [11]. From the electron beam energy and laser photon energy, the maximum energy of the LCS gamma-ray can be estimated by equation (2). In the case of a CO_2 laser with a wavelength of 10.6 μm i.e., $E_p = 0.117$ eV, the maximum energy of the LCS gamma-ray is estimated to be 998±3 keV. As aforementioned, for the precise measurement of Delbrück scattering, it is necessary to use a linearly polarized gamma-ray beam with the energy below the pair creation threshold, 1022 keV. The expected gamma-ray energy (998±3 keV) is slightly below the threshold. The combination of 746-MeV electron beams at UVSOR and the 10.6-μm CO_2 laser satisfies the energy requirement of the precise measurement of Delbrück scattering.

A numerical calculation based on the general formulae of luminosity [12] was performed to evaluate the available gamma-ray flux under the reasonable assumption of laser beam size ($\sigma_{xp} = \sigma_{yp} = 5$ mm). The total gamma-ray flux normalized by laser power and beam current can be evaluated as approximately 6×10^3 ph/W/mA/s. When a collimator with a diameter of 5-mm aperture is used to cut out the high energy part of the LCS gamma-rays, the normalized gamma-ray flux can be evaluated as 1×10^3 ph/W/mA/s with a gamma-ray energy spread of 15 percent in Full Width at Half Maximum (FWHM). When a linearly polarized CO_2 laser with an averaged power of 100 W and the electron beam current of 300 mA is used for the generation of LCS gamma-rays at UVSOR, linearly polarized gamma-rays with a flux of 3×10^7 ph/s and an energy spread of 15 percent in FWHM will be available. The expected accumulation time required to obtain 10% accuracy with the expected gamma-ray flux is about 17 hours. This expected flux is high enough to perform the proposed experiment.

EXPERIMENT

A preliminary experiment was performed to investigate the highest energy and flux of the LCS gamma-ray generated at the UVSOR BL1U with a 10.6-μm CO_2 laser.

Experimental Setup

The experimental setup is shown in Fig. 2. In this experiment, a non-polarized CW CO_2 laser (LASY20D, Access Laser) with an average power of 1.1 W was used. This laser has been used for LCS gamma-ray generation at NewSUBARU [6, 13]. A beam expander consisting of one concave ZnSe lens (*f* = -50 mm) and one convex ZnSe lens (*f* = 200 mm) was used to have the beam waist at the centre of the interaction region. A 5-mm-thick BaF_2 vacuum window (W1 in Fig. 2) was used for injecting the CO_2 laser into the electron storage ring. Another 5-mm-thick BaF_2 vacuum window (W3 in Fig. 2) was used for extracting the CO_2 laser from the electron storage ring. The approximate transmittance of a 5-mm-thick BaF_2 window at the CO_2 laser wavelength (10.6 μm) is 85%. The power of the transmitted CO_2 laser was monitored by a laser power monitor. A $LaBr_3(Ce)$ scintillation detector (3.5 inch diameter × 4 inch) was used as the gamma-ray detector. In this experiment, no collimator was used to measure the energy spectrum of the LCS gamma-rays.

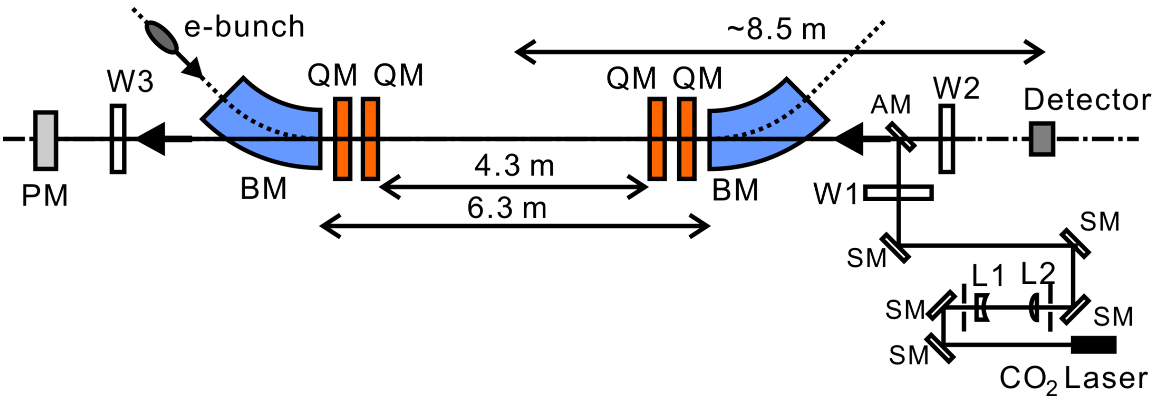

Figure 2: The schematic drawing of the experimental geometry. QM: Quadrupole magnet in the storage ring, BM: Bending magnet in the storage ring, L1: ZnSe concave lens with the focus length of -50 mm, L2: ZnSe convex lens with the focus length of 200 mm, W1 and W3: BaF_2 vacuum window, W2: fused silica vacuum window, SM: silver mirror, AM: aluminium mirror, PM: laser power meter.

Experimental Result

The typical measured spectrum with and without CO_2 laser injection is shown in Fig. 3. The integration time of these measurements was 300 seconds. Even without CO_2 laser injection, the measured spectrum has peaks at 789 and 1462 keV due to the internal activity of the $LaBr_3$(Ce) scintillation detector attributed to ^{138}La. Those peaks are used for energy calibration of the gamma-ray spectrum. To obtain the spectrum of the LCS gamma-rays, the spectrum without CO_2 laser injection was subtracted from the spectrum with CO_2 laser injection. As a result, the difference spectrum shown in Fig. 4 is obtained. As we expected, the maximum energy of the LCS gamma-rays is slightly lower than the pair creation threshold, 1022 keV. Since no collimator was used in this experiment, the gamma-ray energy extends down to energies lower than 200 keV.

The brightness of the LCS gamma-rays was evaluated by taking the average of a 100-keV window near the peak around 950 keV. As a result of the calculation, the brightness was evaluated to be 6×10^{-4} photons/eV/mA/W/s around the peak energy of 950 keV. If we accept 20 percent energy spread, in the case of a 100-W CO_2 laser colliding with a 300 mA electron beam, approximately 4×10^{6}-photons/s gamma-rays could be obtained. This flux is about one order of magnitude smaller than that of the numerical expectation. This mismatch probably comes from the not so good conditions of the CO_2 laser focusing and alignment. However, this flux is still sufficiently high enough for the proof of principle experiment since the integration time required to obtain 10% accuracy is about 130 hours. In future experiments, a more precise adjustment of the focusing and alignment condition of the CO_2 laser will be performed to increase the luminosity of the LCS to increase the gamma-ray flux.

CONCLUSION

In order to perform a precise measurement of Delbrück scattering, high-flux linearly-polarized gamma-rays with the energy below 1 MeV should be provided. The LCS gamma-rays generated in a low energy storage ring with a 10.6-μm CO_2 laser are considered to be a good candidate of the gamma-ray source. A preliminary experiment was performed to check the highest energy and flux of the LCS gamma-rays generated at UVSOR where a 746-MeV electron beam is available. As a result, it was confirmed that the highest energy of the LCS gamma-ray was slightly lower than 1 MeV. And the brightness of the gamma-rays was evaluated to be 6×10^{-4} photons/eV/mA/W/s around the peak energy of 950 keV. In this case, approximately 4×10^{6}-photons/s gamma-rays in 20 percent energy spread will be available with the 100-W CO_2 laser and the 300 mA electron beam. This flux is sufficiently high enough for the proof of principle experiment.

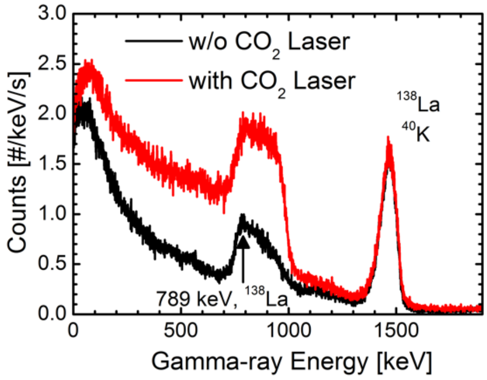

Figure 3: Measured spectrum with and without CO_2 laser injection. The CO_2 laser power was 1.1 W and the electron beam current was 1.3 mA.

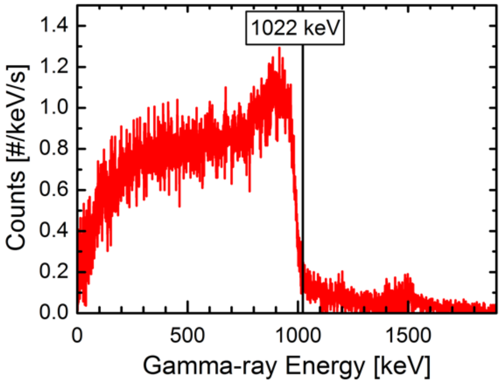

Figure 4: Difference spectrum which was calculated by subtracting the spectrum without the CO_2 laser from the spectrum with the CO_2 laser. The CO_2 laser power was 1.1 W and the electron beam current was 1.3 mA.

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