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An experiment of X-ray photon–photon elastic scattering with a Laue-case beam collider

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ABSTRACT

We report a search for photon–photon elastic scattering in vacuum in the X-ray region at an energy in the center of mass system of $\omega_{\rm cms} = 6.5$ keV for which the QED cross section is $\sigma_{\rm QED} = 2.5 \times 10^{-47}$ m^2. An X-ray beam provided by the SACLA X-ray Free Electron Laser is split and the two beamlets are made to collide at right angle, with a total integrated luminosity of $(1.24 \pm 0.08) \times 10^{28}$ m^{-2}. No signal X rays from the elastic scattering that satisfy the correlation between energy and scattering angle were detected. We obtain a 95% C.L. upper limit for the scattering cross section of 1.9×10^{-27} m^2 at $\omega_{\rm cms} = 6.5$ keV. The upper limit is the lowest upper limit obtained so far by keV experiments.

1. Introduction

Within the framework of classical electrodynamics, light cannot interact with light. However, quantum electrodynamics (QED) predicts that vacuum polarization, a nonlinear effect of quantum fluctuations, intermediates photon–photon elastic scattering. A theoretical cross section was first calculated in 1933 using the Dirac theory [1], and was later done using QED [2]. The leading contribution to the photon–photon scattering cross section is described by a fourth-order Feynman diagram with an electron–positron loop (a box diagram), whose scattering amplitude in the low energy region is strongly suppressed by the electron loop.

When the photon energy in the center of mass system ($\omega_{\rm cms}$) is less than 700 keV, the first-order QED cross section for photons with the same linear polarization state can be described as

$$\left(\frac{d\sigma_{\gamma\gamma\to\gamma\gamma}}{d\Omega}\right)_{\rm QED} = \frac{\alpha^2 r_{\rm e}^2}{(180\pi)^2}\left(\frac{\omega_{\rm cms}}{m_{\rm e}c^2}\right)^6 \times (260\cos^4\theta + 328\cos^2\theta + 580), \quad (1)$$

$$\sigma_{\rm QED} = 3.5 \times 10^{-70}(\omega_{\rm cms}\ [\text{eV}])^6\ \text{m}^2, \quad (2)$$

where α is the fine structure constant, $r_{\rm e}$ is the classical electron radius, and θ is the scattering angle between an incident photon and a scattered photon in the center of mass system ($0 \le \cos\theta \le 1$, $\theta = 0$ corresponds to forward scattering) [2]. The cross section is proportional to the sixth power of $\omega_{\rm cms}$.

Although the inclusive contribution of a box diagram with virtual photons in the MeV region is observed by Delbrück scattering [3] and the high-precision measurement of electron and muon $g-2$ [4], the process with real photons has not ever been directly observed. The observation of photon–photon scattering of real photons would provide solid evidence for vacuum polarization caused by virtual electrons. Furthermore, the search for elastic scattering of real photons has a particular interest as a search for new physics. The photon–photon scattering cross section can be enhanced since new particles predicted by physics beyond the standard model may mediate photon–photon scattering. For example, Axion Like Particles (ALPs), pseudoscalar bosons which have a two-photon coupling constant uncorrelated to their mass, can mediate photon–photon scattering by s or t-channel virtual exchange of ALPs [5–7].

Previous searches have been performed using high intensity optical or infrared lasers [8,9]. However, their sensitivity to photon–photon scattering is suppressed by the tiny QED cross section in the low energy region, $\mathcal{O}(10^{-70})$ m^2 at 1 eV, and by white back-

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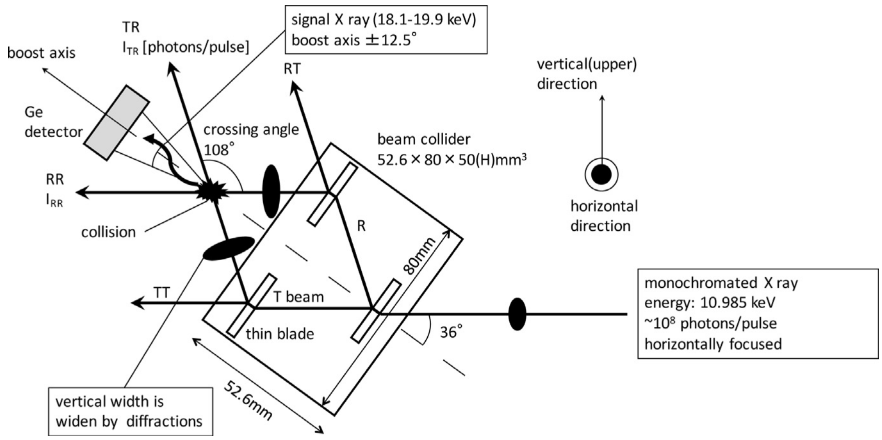

Fig. 1. The schematic of the collision system. Vertical and horizontal directions, which is normal to the optical axis, are also shown.

ground photons generated in their optical systems. By using X rays, the photon–photon cross section can be enhanced by around 23 orders of magnitude compared to the optical region and background photons can be reduced by high precision energy measurement. We performed photon–photon scattering experiments with $\omega_{\rm cms}$ of 6.5 keV and $\sigma_{\rm QED}$ of 2.5×10^{-47} m^2.

In 2013 we performed the first photon–photon scattering experiment in the X-ray region at the Spring-8 Angstrom Compact free-electron LAser (SACLA) [10]. No signal was observed, and we obtained an upper limit on the cross section of photon–photon scattering of $\sigma_{\gamma\gamma\to\gamma\gamma} < 1.7 \times 10^{-24}$ m^2 (95% C.L.) at $\omega_{\rm cms} =$ 6.5 keV [11].

In this paper, we report on the result of a recently upgraded experiment at SACLA with an optimized setup. In this experiment, we replaced the X-ray beam collider with one with thinner blades. This yields a higher diffraction efficiency and smaller sizes of the colliding beams. The beam quality from SACLA has also been improved, with respect to the repetition rate, bandwidth and pulse intensity.

2. Experimental setup and measurement

SACLA generated horizontally-polarized X-ray pulses with $\sim 10^{11}$ photons per pulse, a repetition rate of 30 Hz, a bandwidth of about 50 eV (FWHM), a beam width of 200 μm (FWHM), and a pulse duration less than 10 fs (FWHM) [12]. The vertical and horizontal Rayleigh lengths of X-ray pulses are of the order of 100 m. In this experiment, the energy of the initial X ray was set to 10.985 keV. For extracting X rays with energy within the acceptable bandwidth of our beam collider (100 meV), X-ray beams were monochromatized to 60 meV by two silicon (440) channel-cut monochromators. The pulse intensity was reduced by a monochromatic factor of 60 meV/50 eV $\simeq 10^{-3}$, and the photon number of the monochromatic beams was around 10^8 photons per pulse. The pulse duration of the monochromatic beams was expanded to ~ 30 fs due to the time-energy uncertainty relation. The monochromatic beams were focused to ~ 1 μm (FWHM) in the horizontal direction by an elliptical mirror [13], and the horizontal Rayleigh length is reduced to 20 mm. A detailed explanation of the beamline optics is given in our previous paper [11].

A schematic of the collision system using an X-ray beam collider is shown in Fig. 1. The X-ray beam collider, composed of three thin blades manufactured on a silicon single crystal, diffracts X-ray beams in the transmission (Laue) geometry with the (440) plane at the Bragg angle of 36° [14]. The X-ray beam collider divides the incident beam into four beams (RR, RT, TR, TT beams shown in Fig. 1), two of which (RR/TR) collide obliquely with a crossing angle of 108° and $\omega_{\rm cms}$ of 6.5 keV. The collision is assured spatially and temporally since the lengths of light paths of RR and TR beams are geographically the same [14]. The diffraction efficiencies are higher for the collider with thinner blades because diffracted X rays suffer smaller X-ray absorption within blades. The thickness of the blades is 0.2 mm, and the measured diffraction efficiencies of the colliding beams are 1.55% (RR) and 2.48% (TR). The beam collider was installed in a vacuum chamber evacuated at a pressure of less than 10^{-2} Pa in order to reduce stray photons scattered by the residual gas. The alignment of the chamber in the optical axis was performed by using a manual stage with the precision of 1 mm, much shorter than the Rayleigh lengths. The vertical and horizontal positions, which is normal to the optical axis, were aligned by scanning motorized stages and monitoring the intensity of TR/RR beams passing through the chamber with the precision of less than 0.1 mm.

Since the center of mass system of the two colliding photons is boosted with a Lorentz factor of $\gamma = 1.7$, the spatial distribution of signal X rays is concentrated along the boost axis, and the scattered X rays on the boost axis have higher energy than the incident X ray. A germanium semiconductor detector (CANBERRA BE2825) was used to measure the energy of the scattered X rays [11]. The energy and time resolution of the detector were measured to be 200 eV (1σ, for 26.3-keV X rays) and 80 ns (1σ), respectively. The detector was located on the boost axis of the experimental system as shown in Fig. 1, and detected scattered X rays within a cone with an apex angle of 25° around the boost axis. Within this cone, the signal X rays have an energy between 18.1 and 19.9 keV, and the signal coverage is 17%.

The detector was operated with external triggers synchronized to SACLA. To reject environmental background, a time window was set to ±0.4 μs, which corresponds to $\pm 5\sigma$ of the detector time resolution. The energy was required to be between 17.6 and 20.4 keV, widened from the original signal energy range by the detector energy resolution ($\pm 2\sigma$). The detection efficiency of the detector is $\epsilon = (13.2 \pm 0.3)\%$, as estimated by GEANT4 simulation, and cross-checked by using X-ray sources of ^{55}Fe, ^{57}Co, ^{68}Ge, and ^{241}Am [11]. The uncertainty on the absolute detection efficiency was taken as a systematic uncertainty.

The single-pulse integrated luminosity for obliquely colliding Gaussian beams without angular divergences ($L_{\rm pls}$) is given by the following formula [15],

$$L_{\rm pls} = \frac{I_{\rm RR} I_{\rm TR}}{4\pi \sigma_{\rm h}\sigma_{\rm v}\sqrt{1 + \frac{\sigma_t^2}{\sigma_{\rm v}^2}\tan^2\left(\frac{\theta_c}{2}\right)}} \simeq \frac{I_{\rm RR} I_{\rm TR}}{4\pi \sigma_{\rm h}\sigma_{\rm v}}, \quad (3)$$