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Production of High Energy Photons via Inverse Compton Scattering at SPring-8

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Compton back-scattering of a laser light by the electrons circulating in Synchrotron Radiation (SR) facilities was used to provide high energy polarized photons. For this purpose, a new facility for GeV photon beams in the energy range of $E_\gamma = 1.5 \sim 3.5$ GeV has been constructed at SPring-8. The GeV photons are produced via Compton backscattering, and are used to study the sub-nucleonic structure of the nucleon. The main subject of this project is to search for the quark behavior in the nucleon—the building blocks of nucleons. Fundamental role of quark in nucleon or in a nucleus will be studied as the current topics to reveal the underlying basic principle. This SPring-8 project called Laser-Electron-Photon (LEP) project offers an unique opportunity to study the nucleon structure in view of the quark physics. Using the Compton backscattered photons induced by a short-wave-length laser light, the polarized GeV photons with the maximum energy of 2.4 GeV and a low emittance are generated. This special feature makes real-photon experiments complementary with electron-scattering experiments. The detector called the LEPS sepctrometer is especially designed and constructed to detect the forward events. The results from the latest experiment are shown.

1. Introduction

Synchrotron radiation (SR) was named from having been first generated on earth as a by-product in a high-energy electron accelerator, "synchrotron". This electromagnetic radiation is known to be emitted when electrons with a relativistic velocity are bent in a magnetic field. After the first generation, various methods are invented to obtain photons by using a bending magnet[1,2], a wiggler magnet[3,4], and an undulator magnet[5,6]. Photons obtained in these methods are now commonly used in research in the atomic, molecular, organic, material and medical sciences to probe materials on a molecular level.

There is, however, another way to generate photons in a different mechanism. High-energy real photons produced by means of "inverse Compton scattering" are very useful for such a purpose. The most powerful way to investigate the inside of hadrons is to use electromagnetic probes due to the reduced theoretical complexity of this method. Using collision between laser light and a stored electron beam with energy of 8 GeV, an intense γ-ray beam in the GeV energy region can be produced. The third generation SR rings like SPring-8[7] is especially suitable for this purpose since the electron beam emmitance is extremely small. Recently, a new facility for the photo-nuclear reactions in the energy region of $1.5 \sim 3.5$ GeV started at SPring-8 to serve an important role to study the hadron and nuclear structure by means of photo reactions. In this report, I wish to show the recent results obtained after the successful construction of the LEPS (Laser-Electron-Photons) facility.

2. LEPS facility and Production of high energy photons

After the preliminary investigation of the construction team[8,9], the LEPS (Laser-Electron-Photons) facility was constructed at the beam line BL33LEP for nuclear and hadron physics experiment with primary support from Monbusho (The Ministry of Education, Science, Sports and Culture) and STA (The Science and Technology Agency). Construction of the beam line began in 1998 with the modification of accelerator components. A laser injection system was constructed in the first quarter of 1998 and the experimental hall was completed in March 1999.

A high energy γ beam in the LEPS facility is created by a method of Compton backscattering of a laser light from the 8 GeV electron beam. Thanks to the relativistic effect with a

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very large Lorentz factor $\gamma=16{,}000$, Compton backscattered photons gain an energy of about 7×10^8 times higher than that of incident laser photons. The energy of the Compton backscattered photons is essentially determined as a function of the scattering angle θ:

$$\omega=\frac{4\omega_0E_e^2}{m^2+4\omega_0E_e}\left(\frac{1}{1+\left(\dfrac{E_e^2}{m^2+4\omega_0E_e}\right)\theta^2}\right). \tag{1}$$

The energy of the scattered photon is proportional to E_e^2 and to the laser photon energy ω_0, respectively. The γ-ray divergence is given by a function:

$$f(\theta)=\left(\frac{1}{1+\left(\dfrac{E_e^2}{m^2+4\omega_0E_e}\right)\theta^2}\right). \tag{2}$$

This means that the γ-ray character is determined by the electron beam emittance.

Figure 1 shows an overall view of the LEPS system. The purpose of the beam-line is to inject a laser light beam which collides with the electron beam, allowing the extraction of high-energy photons produced via Compton scattering. High-energy photons are produced in the direction of the 8 GeV stored-electron beam. A bending magnet in the storage ring distal to the collision point is used to measure the energies of knocked-on electrons. Electrons with 4.5–6.5 GeV are tagged in this manner, corresponding to 1.5–3.5 GeV γ-rays. The γ-rays extracted from the ring are guided in the vacuum chamber to the experimental hall. In the experimental hall, there are two hutches along the beam line. The first one, at the exit of the beam tunnel, is the laser hutch and is used mainly for laser injection. The second one is for experimental devices including a spectrometer dipole magnet, drift chamber and plastic scintillation counters.

The first and second hutches are connected with a beam transport pipe. A laser beam injection was made for the first time at this site, and the high-energy photons (LEPS) from the inverse Compton scattering were observed in the laser hutch using a newly-developed lead Tungstate (PWO) scintillation counter[10].

The γ-rays were detected in the calorimetric method. A calorimeter consisting of nine rectangular PWO crystal cells[10,11] was placed behind a sweep magnet in the laser hutch. Energy calibration of each PWO scintillation counter was carried out by measuring gas Bremsstrahlung γ-rays with a maximum enegy of 8 GeV. The measured energy spectra for beam exposures centered on each crystal were convoluted using a known radiation spectrum and a resolution function of the crystal. The energy spectra obtained from nine PWO scintillation counters were summed up to generate the total γ-ray spectrum.

Figure 2 shows the energy spectrum of LEPS, which clearly demonstrates that high-energy photons up to 2.4 GeV are created by inverse Compton scattering between 8 GeV electrons and laser light. The maximum energy calibrated with the photon spectrum from the gas Bremsstrahlung agrees with that calculated using special relativity theory.

The emmitance of the γ-ray beam was also measured using the PWO detector. The horizontal and vertical widths of the γ-ray (LEPS) beam were found to be less than $\sigma_x=3$ mm

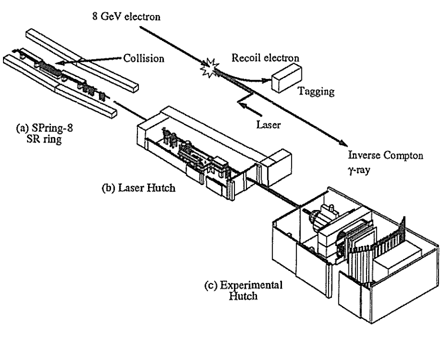

Figure 1. Laser-Electron-Photon (LEP) facility at SPring-8. The facility mainly consists of three parts; (a) Laser-electron collision part in the storage ring of SPring-8, (b) Laser hutch for laser injection, and (c) Experimental hutch. The recoiled electrons are tagged for energy information. A simple schematic explanation on the collision between electron and laser light is inserted in the figure.

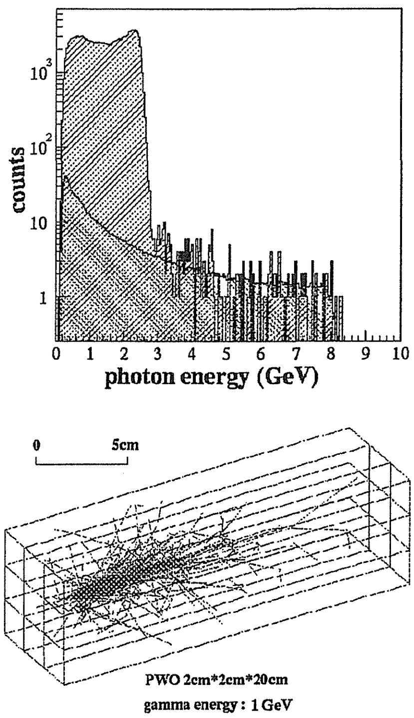

Figure 2. Left: Energy spectrum of the Inverse Compton γ-rays obtained via the head-on collision between high energy 8 GeV electron and Argon laser-light. The γ-ray spectrum is compared with those of the Bremsstrahlung γ-rays due to the collision between 8 GeV electron and the residual gas in the storage ring. Right: A schematic principle of the operation of the PWO detector. The PWO detector consists of 9 segmented lead tungstate ($PbWO_4$) crystal. Electron-positron showers induced by a high energy γ-ray are shown.

and $\sigma_y = 2$ mm, respectively, at the distance of 40 m from the collision point. These values are consistent with those expected using a Lorenz factor of $E_e/m_ec^2 = 16{,}000$, demonstrating the extremely low emittance of the 8 GeV electron beam in the storage ring at SPring-8[7].

3. LEPS Spectrometer

Figure 3 shows the LEPS spectrometer to analyze the charged particles at forward angles. The LEPS spectrometer mainly consists of one dipole magnet with a large aperture, and three drift chambers, and TOF scintillation counters. The dipole magnet is used to bend the charged particles produced by photo-nuclear reactions. One of the three drift chambers is located between the target and the dipole magnet. All the drift chambers are used to determine the position of particle trajectories. The ray-tracing technique is fully employed to determine the trajectories of charged particles. The TOF scintilation counters serve to identify the particle mass through the measurement of the time-of-flight (TOF).

In the case of the ϕ meson photo-production, a ϕ meson decays into $K^+ + K^-$ pairs. This situation is also illustrated in **Fig. 3**. For the ray tracing, the measured magnetic field is used. The achievable resolution of this LEPS spectrometer is already tested to observe the electron-positron pair production, whose energy distribution is well predicted in the QED theory. We conclude that a resolution of 30 MeV is easily obtained with the present setup of the spectrometer.

4. Recent Achievements

Actual beam time started from 17 May 2000 after one year preparation including all the administrative permission to use the LEP facility at SPring-8. The intensity of photon beam amounts to 2.5×10^6/second with a beam size less than 1 cm at the experimental hutch. Using the LEP spectrometer consisting of a dipole magnet, three drift chambers (each including 5 wire planes), and TOF scintillation counters, a full tacking technique for tracing photo-produced particles was applied. The upper part of **Fig. 4** shows the loci for the positively charged particles. Events for protons, K^+ mesons and π^+-mesons are observed. The lower part of **Fig. 4** is the locus of the negatively charged particles corresponding π^--mesons. We have confirmed that if we pose a gate to the K^+ events, π^--meson events remain. This means that we can easily observe the photo Λ production events.

However, after many trial of the background reduction, the locus corresponding to K^- mesons becomes clear, and we can produce the invariant mass spectrum for events of the ϕ-meson. The results are shown in **Fig. 5**. **Figure 5**(a) shows the spectrum of particle identification for the photo-particle productions from the CH_2 and C placed at the target

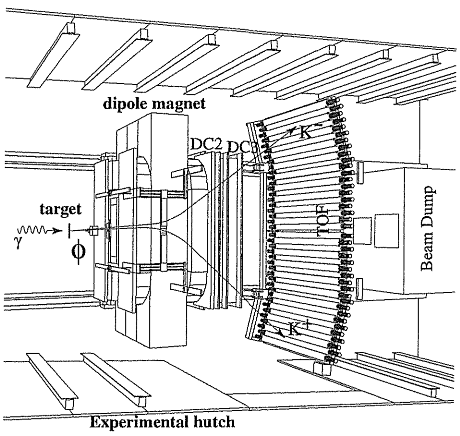

Figure 3. Top view of the spectrometer system (LEPS) in the experimental hutch. The spectrometer mainly consists of a dipole magnet, drift-chambers, and scintillation counters for TOF measurement. High-energy γ-rays coming from the left side are stopped at the beam dump (in the right side of the figure). A typical event of $K^+ + K^-$ pairs for ϕ-meson production is shown.

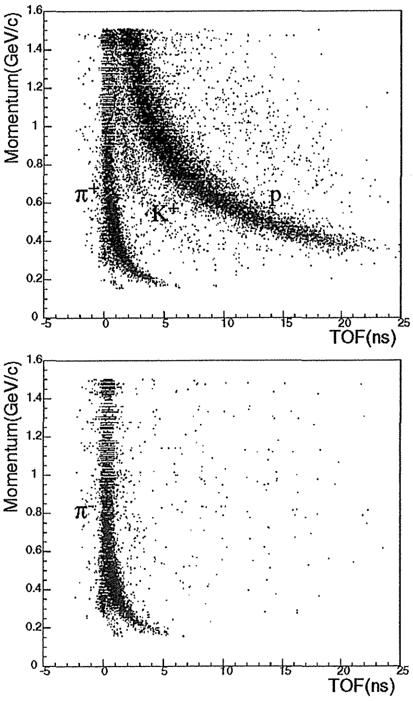

Figure 4. Scatter plot for the particle identification. (a) Particle events with positive charged particles. (b) Events with negative charges.

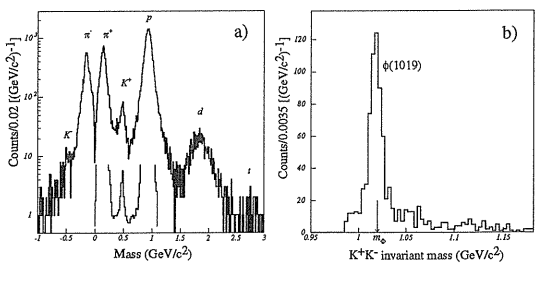

Figure 5. (a) Spectrum for particle identification. Peaks from reconstructed masses are shown for runs with the CH_2 and C targets. (b) $K^+ + K^-$ invariant mass spectrum.

position indicated in **Fig. 3**. The production of the $K^+ + K^-$ particle pair is relatively small. The yields of K^+ particles are much higher than those of K^- particles. This indicates that K^+ mesons are produced associated with the Λ particles. Much higher yields are pion production, which is one order of magnitude higher than those of K^+ particles. The π^+ and π^- mesons are produced from the decay of ρ-mesons, Δ excitation, and other processes. An interesting observation is the fact that the difference of π^+ and π^- meson yields are very small.

Another feature of the mass identification spectrum is that the proton yields is high. This is due to the recoiled protons in the process $\gamma p \rightarrow X + p$, where X stands for the produced particle with the energy $E \approx 0$. High energy deuterons are also observed in the spectrum. The deuterons can be produced in the cascade process, where a high energy proton picks up a neutron in the nucleus C. Tritons are also observed. The yield ratio of all the particles should be understand with the help of theoretical calculations. At least, we can address a question why the π^+ and π^- meson productions are rather equal.

By posing the coincidence gate for both K^+ and K^- mesons, K^+K^- invariant mass spectrum was made. **Figure 5** shows the result. The ϕ meson mass is correctly reproduced at 1.019 GeV.

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