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GENERATION OF POSITRONS VIA PAIR-CREATION OF COMPTON SCATTERED GAMMA-RAYS

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Abstract

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Abstract

The important role of positron (e^+) polarization in future linear colliders is discussed in terms of effective polarization, which is closely related to the clear observation of interesting reaction processes in e^-e^+ collision. In order to verify our proposed method that highly polarized e^+ can be generated through Compton scattering of laser light off a relativistic electron (e^-) beam, we attempted an experiment to prove the principle and observed e^+ productions for the first time. It was found that the production rates of e^+s, e^-s, and γ-rays are not only consistent with each other but also in reasonable agreement with numerical estimations.

1 INTRODUCTION

It is generally understood that for a future electron (e^-)-positron (e^+) collider, e^- polarization is useful in order to investigate the details of the standard model by enhancing certain types of interactions or by suppressing dominant backgrounds due to the reaction process $e^-e^+ \to W^-W^+$. Within the framework of the standard model, high energy e^- and e^+ always annihilate each other in their combination of $e^-{}_Le^+{}_R$ or $e^-{}_Re^+{}_L$, with the suffix L(R) representing left(right)-handed helicity. Thus, if only an e^- is polarized, e^+ helicity is automatically determined as opposite to that of the e^-. In the following, we simply denote only L or R for e^-e^+ collision. It is well known that if right-handed helicity is chosen for an e^-, thus leading to the combination R-L, contributions of W^-W^+ productions which often cause serious backgrounds can be significantly suppressed. However, since the magnitude of e^- polarization is not 100%, another combination L-R is necessarily mixed into the combination R-L, and the ability to suppress backgrounds is thus deteriorated. This difficulty can be overcome by polarizing the e^+ as well as the e^-. Indeed, we have pointed out the important role of e^+ polarization to examine the details of the standard model and the exotic phenomena beyond the standard model[1–3].

Recent progress made on semiconductor photocathodes has accounted for the development of high-intensity polarized e^- beams with a polarization greater than 70%[4–6], while the development of polarized e^+ beams with sufficient intensity and magnitude of polarization continues encountering numerous technical difficulties because e^+ must be artificially created. In 1996, we proposed a new method[7] whereby the Compton scattering of circularly polarized laser light off a relativistic e^- beam permits the creation of polarized γ-rays, which subsequently pair-create highly polarized e^+s, as illustrated in Fig.1. To verify this method, we designed an experiment to prove its principle by generating a polarized e^+ and measuring the e^+ polarization in the successive three quantum processes, i.e., Compton scattering, pair creation, and Bhabha scattering. In the present experiment, as a first step, we observed γ-rays and e^+s using a 1.26 GeV e^- beam and a non-polarized laser light.

The future linear collider JLC requires extremely high intensity e^+ beams with a complicated multi-bunch structure[8]. In compliance with our method, we designed the JLC polarized e^+ source[9–13]. In 1979, Balakin and Mikhailichenko had proposed producing polarized γ-rays by utilizing a high intensity e^- beam of about 150 GeV which propagated through a long helical undulator of about 150 m[14,15]. It should be emphasized that our proposed system is relatively compact as well as based on well-understood QED processes. Therefore, it ensures reliable estimations of the production rates and the magnitude of e^+ polarization, even though there still remain several technically challenging problems with respect to a high intensity e^- linac and multi-laser systems[13].

In sec.2, we discuss the roles of e^+ polarization in terms of an effective polarization, a transverse polarization, and some considerations relating to physics. In sec.3, we present the first results of observing e^+ production on the basis of the proposed method of laser-Compton scattering. In sec.4, various properties of e^- and laser beams are described, and the luminosity of the e^- laser collision is derived so as to compare the data with the numerical predictions. Section.5 is devoted to conclusions and future prospect.

2 ROLES OF POSITRON POLARIZATION

As is well known, the effective polarization P_{eff} of $\mathrm{e}^-\mathrm{e}^+$ interactions is defined as

$$P_{\text{eff}} = \frac{P_1 - P_2}{1 - P_1 P_2} \tag{1}$$

where P_1 and P_2 stand for the e^- and e^+ beam polarizations respectively: $P_1 = 1$ ($P_2 = -1$) represents 100% polarization for a right-handed e^- beam (a left-handed e^+ beam). The eq.1 clarifies that P_{eff} can be significantly improved if an e^+ beam as well as an e^- beam is polarized[16,17]. Here assuming that errors of measuring the polarization both for e^- and e^+ beams are 1% and the e^- beam has the polarization of 90%, and we obtain P_{eff} and its error $\Delta P_{\text{eff}}/P_{\text{eff}}$ as a function of the e^+ polarization as shown in Fig.2. For example, if $P_2 = -80\%$ in addition to $P_1 = 90\%$ is achieved, we can obtain the high value of $P_{\text{eff}} = 99\%$ and the considerably small error $\Delta P_{\text{eff}}/P_{\text{eff}} = 0.0016$, which can help us to measure some physical parameters very precisely as compared with the case of only e^- polarization $P_1 = 90\%$. This also enhance the signal-to-noise ratio in observing new particles.

Furthermore, some models beyond the standard model predict interesting processes emerging in R-R or L-L combination of polarization. For example, $\tilde{\mathrm{e}}^-\tilde{\mathrm{e}}^+$ pair production through the $\tilde{\chi}^0$ exchange diagram predicted in a super-symmetry model can be observe R-R combination of beam polarization. To have both e^- and e^+ beam polarization is very useful to observe such processes, because by choosing R-R or L-L beam polarization, there is strong suppression of $\mathrm{f}\bar{\mathrm{f}}$ production through annihilation diagrams as well as the $\mathrm{W}^-\mathrm{W}^+$ production.

The importance of transverse polarization was also pointed out[18]: If both e^- and e^+ have the transverse polarization described as the linear combination of longitudinal polarization, unknown phenomena emerging in the R-R or L-L combinations might be enhanced by the allowed processes of the standard model, i.e., the combination of R-L or L-R through interference between different combinations of longitudinal polarization of e^- and e^+, i.e., R-R and L-R(R-L) or L-L and L-R(R-L). Consequently the controllability of the spins of an initial e^+ beam as well as an e^- beam should be of great importance in a linear collider experiment where new phenomena should be clearly discovered.

3 EXPERIMENT

3.1 DIFFERENTIAL CROSS SECTIONS

We attempted to calculate various quantities that are necessary for designing experimental facilities to observe production and polarization of positrons. Utilizing GRACE[19], we obtain the differential cross section of the Compton scattering process that circularly polarized laser light of 2.33 eV with a helicity $h = 1$ is scattered by an unpolarized e^- beam of 1.26 GeV. Fig.3 represents (a) the differential cross section and (b) the polarization for Compton scattered γ-rays as a function of the γ-ray energy. As seen in Fig.3, high polarization (helicity $h = -1$ in this case) is expected for the back-scattered γ-rays near the high energy end of the spectrum. The total cross section of Compton scattering is obtained to be 637 mb. Taking into account the energy and polarization distributions given in Fig.3, we calculated the differential cross section of pair-creation and the e^+ polarization as shown in Fig.4 which clarifies that the polarization of 80% can be achieved, if e^+s with energy higher than 23 MeV are selected. Since the cross section of pair-creation is proportional to the square of the charge number of a nucleus, Z^2, we present the cross section normalized by Z^2 in the Fig.4. On the other hand the ionization energy loss of e^+ per nucleus is, roughly speaking, proportional to the charge number Z. Consequently material with a large Z is suitable as the target material, and thus we adopt a thin tungsten (W) target.

3.2 APPARATUS AND DATA TAKING

The schematic view of the experimental set-up[22,23] is depicted in Fig.5. Extracted e^- beams of 1.26 GeV/c with intensity of $N_{e^-} = 6 \times 10^9$ e^-/bunch and time width of 20 psec are provided every 1.28 sec from the ATF damping ring[24] which has been constructed as a test facility for linear colliders. We used a pulse-laser, Nd:YAG laser, Continuum NY81C-10 with power of 200 mJ in a 7 nsec FWHM pulse width at the wavelength of 532 nm (the second harmonic). In the present experiment, as a first step to prove the principle of our method, we did not measure e^+ polarization but verify e^+ production. Hence non-circularly-polarized laser light is guided from the laser generator which is set outside a radiation shield to a collision point after reflections on the 5 mirrors located in air as shown in Fig.5 and a small prism located in vacuum of the beam pipe. Since the laser light travels through one prism, two lenses and one sapphire-window and is reflected on five mirrors, the laser intensity is reduced to 65% at the collision point and the focal length for this optics becomes rather long, i.e., 454 cm. A crossing angle between e^- and laser beams is $\varphi = 7$ mrad.

Immediately after Compton scattering, initial e^- beams are bent away by means of a bending magnet and then, back scattered γ-rays are injected on the 1 mm thick W-target to pair-create e^-s and e^+s. To separate e^+s from e^-s, a pair of magnets called "the separation-magnet" is specially designed and located just after the W-target. The separation magnet effectively separate e^+s with the energy higher than about 23 MeV so as to yield highly polarized e^+s. The target thickness of 1 mm was chosen to compromise following two conditions. Firstly, production rate of e^+s increases as target thickness increase. On the other hand, the e^+ transportation efficiency through the separation-magnet decreases when we employ thick target, because effect of multiple scattering of the produced e^+s in the target material increases. The appropriate target thickness was estimated using a simulation program EGS4[20] for electromagnetic interactions of charged particles in materials. The e^+ transportation efficiency through the separation-magnet is estimated by Monte Carlo simulation as given in Table 1 for magnet currents $I = 14 - 20$ A. Spin-flip effect in the target material was checked by modifying the EGS4 with the help of the HELAS utility[21] and found to be around 1%.

Since the experimental area was exposed to high backgrounds form the accelerator, we made use of, for γ-ray measurement, an air Cherenkov counter with the refractive index of $n = 1.0003$. This counter is insensitive to charged particles with the kinetic energy below the threshold of 20.4 MeV. In a Pb-plate of 5 mm thickness placed at the entrance of the air Cherenkov counter, 60% of Compton scattered γ-rays are converted to e^-s and e^+s. An e^- (e^+) which has kinetic energy well above the threshold emits 0.48 Cherenkov photons per 1 cm. For e^+ measurement, we adopted four acrylic Cherenkov counters with $n = 1.48$. The threshold energy of those counters is 0.183 MeV. A positron generate Cherenkov photons of 447 per 1 cm leading to 59 photoelectrons on the photocathode. The size of an acrylic radiator is 10 mm in diameter and 50 mm in length.

The geometrical overlap of the laser lights and e^- beams was checked on a screen monitor by remote-controlling the angles of two reflection mirrors whose minimum pitch is about 100 μrad, thus permitting to the adjustable precision of 52 μm for the laser spot at the collision point. To synchronize the laser pulse and the e^- bunch, we utilize the timing signal from the master oscillator which controls the whole system of the accelerator. The Q-switch of the laser generator is triggered by the signal from the master oscillator through a digital delay module. Thus we adjust the delay time by comparing the timing of laser pulse observed by a photodiode at the exit of laser generator with the timing signal from the beam position monitor located near the collision point. Finally, fine adjustment is done by maximizing the intensity of back scattered γ-rays as a function of delay time.

To suppress systematic errors due to long term variation of the related parameters of the accelerator, laser systems, detectors and related electronics, we switched on and off the laser beam alternatively to each e$^-$ bunch and measure the pulse height (ADC counts) of the Cherenkov counters. Since the ADC count of air Cherenkov counter is proportional to the sum of backscattered γ-rays and machine related background, there should be sharp peak in the laser-off signal at the 0 ADC count if no background emerges. Indeed fig.6(a) indicates the relatively narrow laser-off peak which is separated well from the laser-on distribution corresponding to gamma-ray production. In a similar manner, e$^+$ signals were observed as shown in Fig.6(b). Unfortunately e$^+$ detectors are subject to large backgrounds because acrylic Cherenkov counters have a lower threshold and thus, a large overlap between the laser-on and laser-off signals is observed. Using π^- beams of 2 GeV/c provided from the proton synchrotron at KEK, we calibrated the acrylic Cherenkov counters. Then we derived number of e$^+$s on the counters from the difference between laser-on and laser-off signals. The number of observed e$^+$s per bunch as a function of the current of the separation magnet is shown in Fig.7. In order to confirm the reliability of our measuring system, we also observed e$^-$s by reversing the polarity of magnetic fields. The number of observed e$^-$s is 0.73 ± 0.02 for $I = 18$ A which, as demonstrated in Fig.7, is in good agreement with the number of e$^+$s/bunch for $I = 18$ A, i.e., 0.75 ± 0.03. Furthermore we checked that no difference were observed between laser-on and laser-off signals, if the W-target and the magnetic field of the separation magnet were not available.

4 NUMERICAL PREDICTIONS

Horizontal and vertical emittances of the e$^-$ beam were measured to be $\epsilon_{\mathrm{x}} = 2.6 \times 10^{-9}$ rad-m and $\epsilon_{\mathrm{y}} = 6.5 \times 10^{-11}$ rad-m. Using these values and a Twiss parameter β at the collision point, i.e., $\beta_{\mathrm{x}} = 2.4$ m and $\beta_{\mathrm{y}} = 1.5 \times 10^2$ m, we obtain the beam size in the transverse direction as $\sigma_{\mathrm{ye}^-} = 97\,\mu$m. However, taking into account a dispersion $\eta_{\mathrm{x}} = 0.6$ m and a momentum spread $\Delta p/p = 7.5 \times 10^{-4}$, we obtain a much larger horizontal beam size $\sigma_{\mathrm{xe}^-} = 440\,\mu$m. The e$^-$ bunch-width 20 psec results in the longitudinal beam size of 6 mm. On the other hand, the laser beam size is $\sigma_{\mathrm{x}\gamma} = 0.85$ mm and $\sigma_{\mathrm{y}\gamma} = 1.0$ mm in the transverse direction, and $\sigma_{\mathrm{z}\gamma} = 89$ cm in the longitudinal direction. Assuming a Gaussian beam shape both for e$^-$ and laser beams, luminosity $\mathcal{L}$ is represented as

$$\mathcal{L} = \frac{N_{\mathrm{e}^-} N_{\mathrm{laser}}}{2\pi\sqrt{\sigma_{\mathrm{ye}^-}^2 + \sigma_{\mathrm{y}\gamma}^2}\sqrt{\cos^2\left(\frac{\varphi}{2}\right)\left(\sigma_{\mathrm{xe}^-}^2 + \sigma_{\mathrm{x}\gamma}^2\right) + \sin^2\left(\frac{\varphi}{2}\right)\left(\sigma_{\mathrm{ze}^-}^2 + \sigma_{\mathrm{z}\gamma}^2\right)}} \tag{2}$$

where $N_{\mathrm{e}^-} = 6 \times 10^9$ represents e$^-$ population in a bunch, and N_{laser} represents the number of laser photons in a laser pulse at the collision point which can be calculated as 200 mJ × 0.65 = 130 mJ. Using the parameters of the e$^-$ and laser beams given above, we obtain the luminosity for the laser-e$^-$ collision to be 4.5 mb^{-1} leading to numbers of γ-rays generated through the collision, i.e., 3.1×10^3. According to EGS4 simulations, the conversion efficiency from γ-rays to e$^+$ on the W target of 1mm thickness is obtained to be 7.0% so that the total number of e$^+$s per one collision is predicted as 2.2×10^2. Using the transportation efficiency of the separation magnet, we estimate number of e$^+$s at the exit of the separation magnet. Then, taking account of the acceptance 0.24 for the whole acrylic counters, we can predict the expected number of e$^+$s. In Table 1, we summarize experimental data and expected numbers of e$^+$s together with the transmission efficiency for the current $I = 14, 16, 18, 20$. Fig.7 demonstrates measured and expected numbers of e$^+$ per bunch as a function of the current I. Actually the predicted values are almost twice as large as the measured ones: this systematic effect is due to e$^-$ beam jitter and time fluctuations of laser beams as well as electronics systems.

5 CONCLUSIONS AND FUTURE PROSPECT

We observed e$^+$ production for the first time via successive two quantum processes, i.e., Compton scattering and pair-creation, and confirmed that the production rates of e$^+$s, e$^-$s and γ-rays are consistent with each other, although experimental precision of determining various properties of both e$^-$ and laser beams are not sufficient. Reasonable agreement between the experimental data and the numerical estimation verifies that our proposed method is promising for generating polarized positrons. It should be noted that our method is based on the well understood QED processes and thus further upgrading or improvement of facilities can be quantitatively estimated. Actually through the present experiment, we have accumulated numerous technical information on laser and e$^-$ beam collisions which helps to improve significantly signal-to-noise(S/N) ratio for attaining our goal of measuring the e$^+$ polarization by Bhabha scattering on a magnetized iron. Indeed, to measure the e$^+$ polarization with reasonable precision via successive three quantum processes, we are designing a special off-axis mirror to achieve head-on collision of laser light and e$^-$ beam as well as strong focusing of laser lights so that the luminosity is significantly increased, thus leading to the improvement of S/N ratio over 100 times. Furthermore, fine tuning of the damping ring and various improvements to increase the beam intensity will be greatly helpful to achieve our final goal.

Future colliding experiments at JLC require extremely high intensity e$^+$ beams, i.e., $7\times10^9 e^+$s/bunch with highly complicated time structure, so called a multi-bunch beam. The conceptual design[13] clarifies that our proposed method is also applicable to polarized positron production at JLC if we provide in Compton scatterings a high-intensity e^- beam of $10^{11}e^-$/bunch and high energy laser lights of 10J / pulse. The technical details on the realistic design are published in ref.[13,25]. It should be remarked that, as discussed in ref.[18], the transverse polarization in the collider experiment might be of great importance to reveal various new phenomena and thus, we have to measure with reasonable accuracy three components of a polarization vector. We found that a method on the basis of laser-Compton scattering can be utilized again to determine both longitudinal and transverse polarizations by measuring the asymmetry of angular distributions of back-scattered γ-rays[26]. Further discussions of $e^\pm$ polarimetry at a linear collider will be discussed elsewhere.

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Magnet current [A]	14	16	18	20
Transportation efficiency	0.019	0.017	0.013	0.010
Expected No. of e^+s pass the magnet	8.41	7.52	5.75	4.43
Expected No. of e^+s on the detector	1.98	1.78	1.36	1.04
Detected No. of e^+s (experimental)	1.13 ± 0.04	0.93 ± 0.03	0.75 ± 0.03	0.66 ± 0.02

Table 1
Transportation efficiency of the separation magnet and expected numbers of e^+s traveling through this magnet are indicated as a function of current. Expected and detected numbers of e^+/bunch are also given.

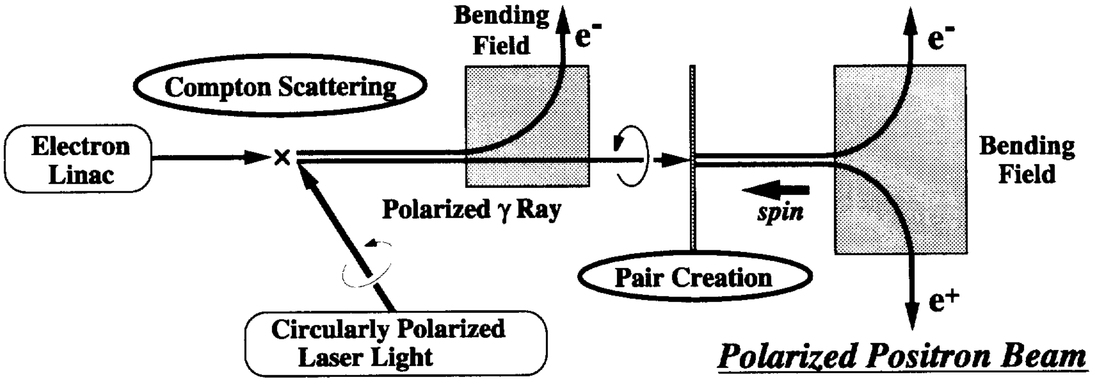

Fig. 1. Schematic illustration of a polarized positron source via Compton scattering of circularly polarized laser lights off relativistic e^+ beams.

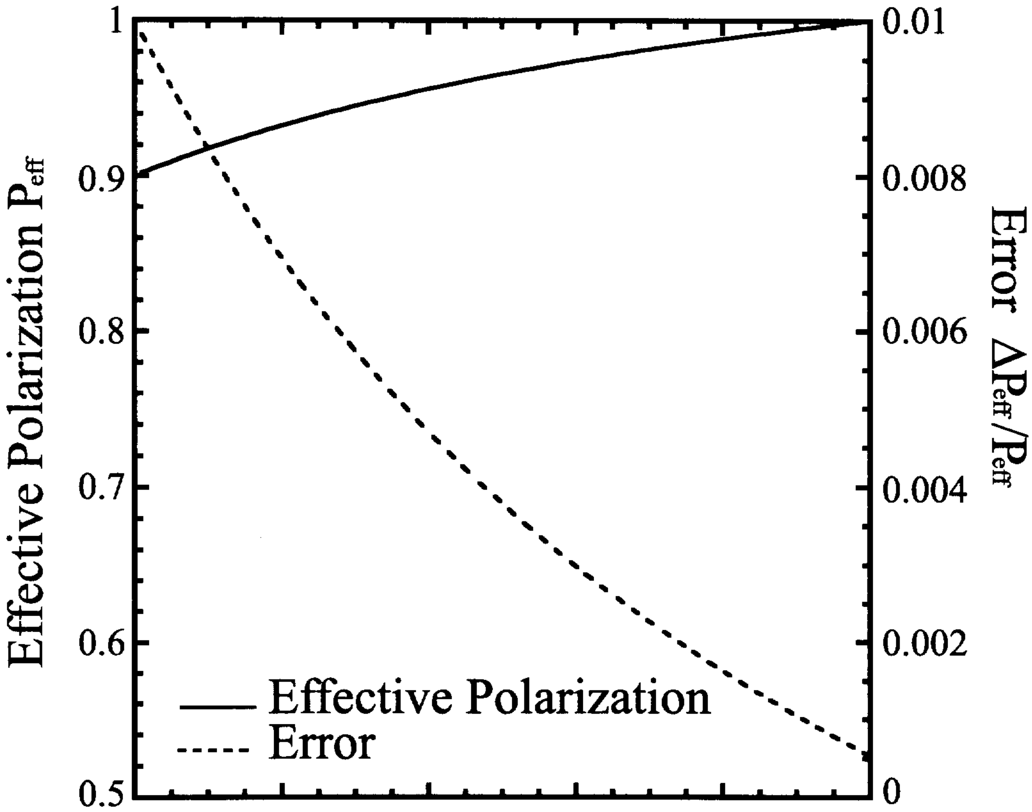

Fig. 2. Effective polarization P_{eff} and its relative errors $\Delta P_{\text{eff}}/P_{\text{eff}}$ as a function of e$^+$ polarization. Here we assume that errors of measuring the polarization both for e$^-$ and e$^+$ beams are 1% and the e$^-$ beam has the polarization of 90%.

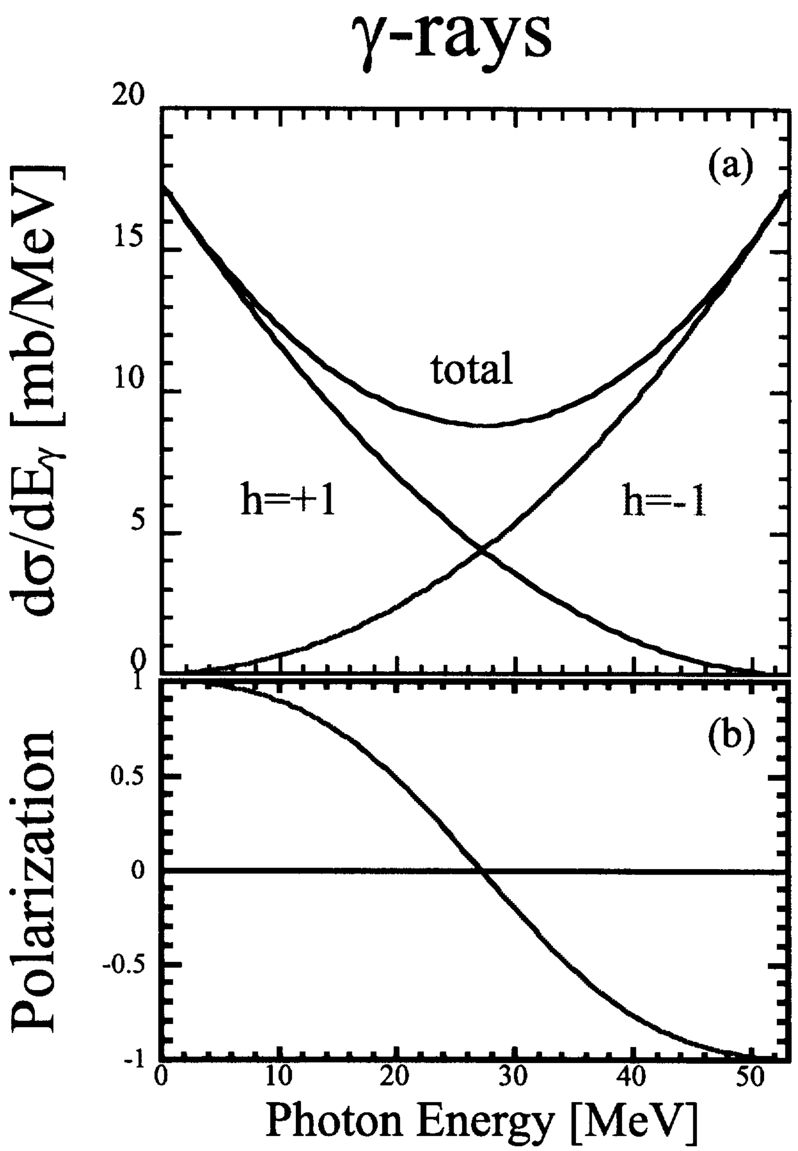

Fig. 3. Differential cross section of the Compton scattering. Circularly polarized laser light of 2.33 eV with a helicity $h = 1$ is scattered by an unpolarized e^- beam of 1.26 GeV. (a)Differential cross section. Here $h = +1(-1)$ corresponds cross section having scattered γ-rays of $h = +1(-1)$. The total shows sum of them. (b) γ-ray polarization as a function of the γ-ray energy.

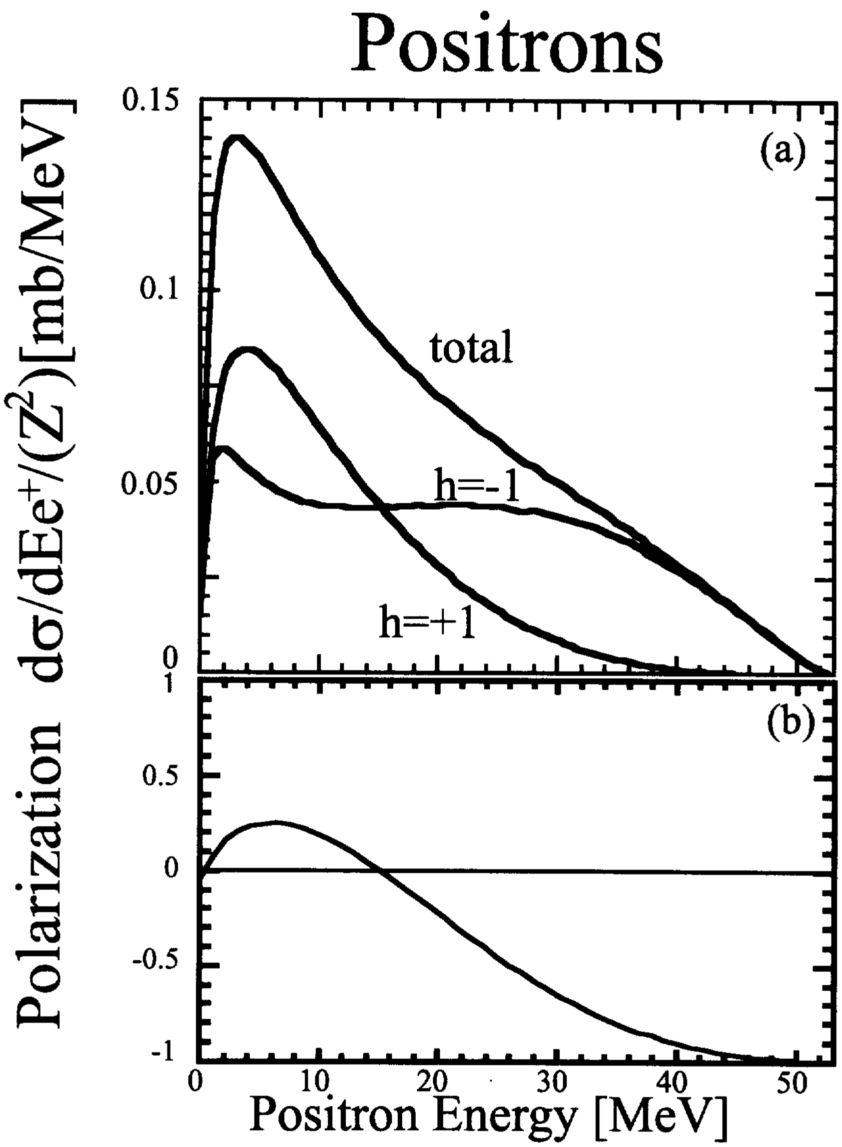

Fig. 4. (a)Differential cross section of pair-creation as function of positron energy. Cross section is normalized by the square of the charge number of the nucleus Z^2. Here $h = +1(-1)$ corresponds cross section to produce e^+s of $h = +1(-1)$. We take into account the energy and polarization distributions of incident γ-rays given in Fig.3. (b) e^+ polarization as a function of the e^+ energy.

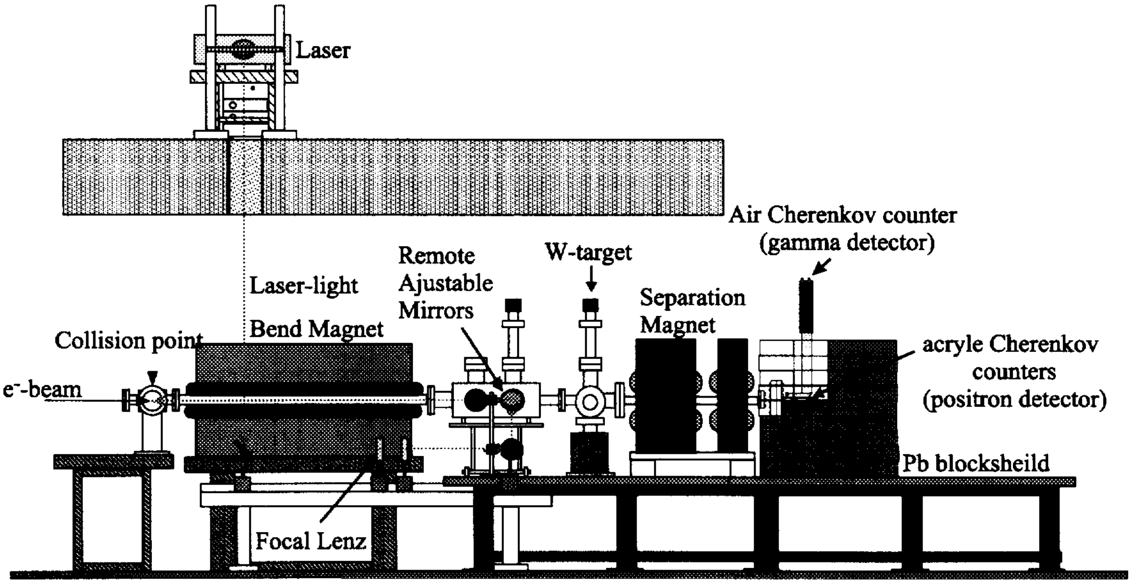

Fig. 5. Side view of the experimental set-up so as to measure generated $e^{\pm}$s and γ-rays.

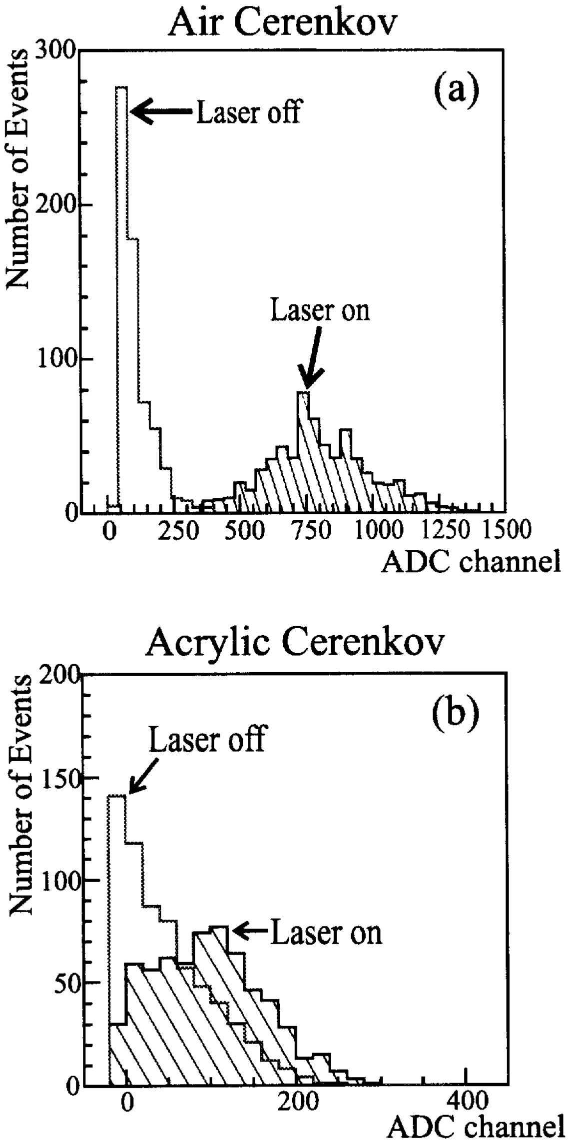

Fig. 6. Number of events as a function of pulse height (ADC counts) (a) of the air Cerencov counter for γ-ray detection and (b) of an acrylic Cerencov counter for e^+ detection. Shaded (white) histgrams show events with laser-on (laser-off).

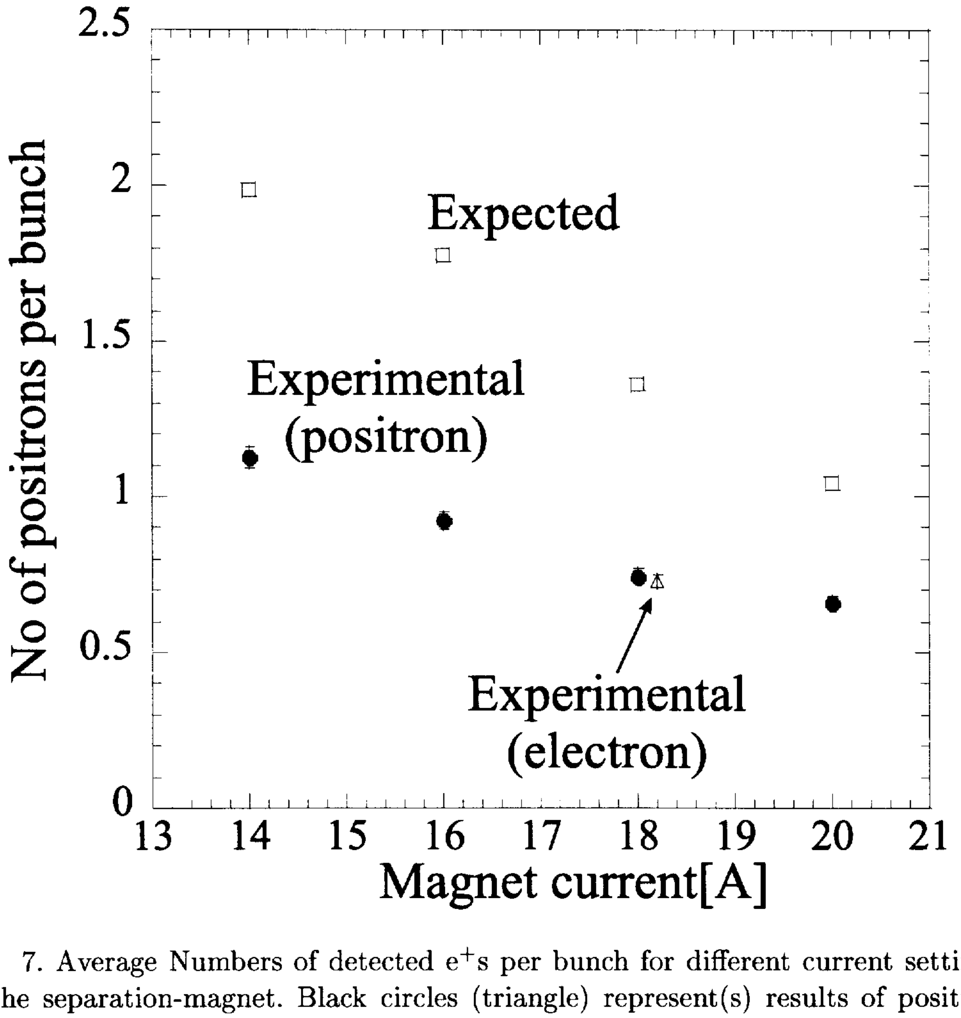

Fig. 7. Average Numbers of detected e$^+$s per bunch for different current settings of the separation-magnet. Black circles (triangle) represent(s) results of positron (electron) experiment. Squares represent expectation (see text).