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# Parity-Violating Asymmetry in Exclusive Photoproduction of Lepton Pairs from Protons

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The neutral-current effects in the exclusive lepton pair production with a circularly polarized photon beam on a proton target are discussed. We derive the parity-violating asymmetry for the lepton produced by right- and left-handed photons. It is expressed in terms of the well-known electromagnetic and weak form factors of the nucleons. Numerical calculations are given in the standard Weinberg-Salam model. We show the asymmetry as a function of the lepton energy in some kinematical configurations. The neutral-current effects are of order $10^{-7}\sim10^{-5}$ in the lepton production angle range from 1° to 10° for the incident photon energy of 20 GeV.

## § 1. Introduction

Parity violation in deep-inelastic scattering of longitudinally polarized electrons from unpolarized deuterons has been observed at SLAC[1] and the results are consistent with the Weinberg-Salam model.[2] It is now of particular interest to determine the form of the electron-quark neutral-current couplings.[3] These interactions have also been studied in parity violation in atomic physics,[4),5] while the experimental situation for bismuth is still confusing.[5] In connection with the weak neutral current of the electron, we have investigated the parity-violating asymmetry in the inclusive lepton pair production with circularly polarized photons in our previous publication.[6]

For the theoretical analysis of *inclusive* reactions, however, we inevitably use the quark-parton model. It is therefore necessary to examine *exclusive* reactions in order to give the predictions in a parton-model-independent way. In the present paper, we discuss the parity-violating effects in the *exclusive* lepton pair production with circularly polarized photons from unpolarized protons. The cross section for this process is described in terms of the electromagnetic and weak form factors of the proton. Furthermore, the weak-neutral-current form factors can be related to the electromagnetic and weak-charged-current form factors of the nucleons, by neglecting the contribution of the strange and charmed quarks in the nucleon.[7] So we have the advantage of using the nucleon form factors which have already been well established by the other experiments.[8),9]

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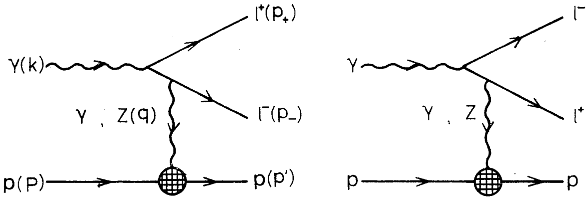


Fig. 1. Feynman diagrams for the exclusive photoproduction of lepton pairs via the Bethe-Heitler mechanism.

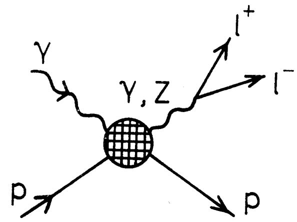


Fig. 2. Compton-type diagrams for the lepton pair photoproduction.

In unified gauge theories, the weak neutral vector boson exchange processes as well as the photon ones contribute to the photoproduction of lepton pairs, and a parity-violating asymmetry is, therefore, expected. The relevant Feynman diagrams are illustrated in Figs. 1 and 2, which correspond to the Bethe-Heitler and Compton-type processes, respectively. The naive perturbation calculations straightforwardly show that the magnitude of the Compton-type amplitude is about 10 percent of that of the Bethe-Heitler one for the forward production of lepton pairs at the incident photon energy of 20 GeV or less than that. Accordingly, the Compton-type diagrams are ignored in the present paper.

In § 2 we derive the differential cross section for the exclusive photoproduction of lepton pairs on a proton target, and we define the parity-violating asymmetry of leptons produced by right- and left-handed photons. It is expressed in terms of the electromagnetic and weak form factors. The numerical results are given in § 3 for the Weinberg-Salam model.[2] The parity-violating asymmetry is shown as a function of the electron (muon) energy in some kinematical configurations. We find that the parity-violating effects are of order $10^{-7}\sim10^{-5}$ in the different configurations for the incident photon energy of 20 GeV. The numerical calculations are also performed for the hybrid model.

## § 2. The cross section and asymmetry for the exclusive photoproduction of lepton pairs from protons

Let us consider the lepton pair production with a circularly polarized photon beam on a proton target:

$$\gamma_\lambda(k)+p(p)\to l^+(p_+)+l^-(p_-)+p(p')\,, \tag{1}$$

where the quantities in parentheses denote four-momenta of the corresponding particles, and $\lambda$ is the helicity of the incoming photon.

The relevant interaction Lagrangian*) we use is

$$L_I=e[-i\bar{\psi}\gamma_\mu\psi+J_\mu^{\mathrm{em}}]A_\mu+g_Z[i\bar{\psi}\gamma_\mu(g_V+g_A\gamma_5)\psi+J_\mu^Z]Z_\mu\,, \tag{2}$$

*) The Pauli-Dirac metric and conventions are used.

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where $\psi$, $A_\mu$ and $Z_\mu$ stand for the fields of the lepton, the photon and the weak neutral vector boson, respectively. $J_\mu^{\text{em}}$ and $J_\mu^Z$ are the electromagnetic and weak neutral currents of hadrons. $e$ is the proton charge, and $g_V$, $g_A$ and $g_Z$ are neutral weak coupling constants depending upon gauge models. We also assume the interaction (2) is time-reversal-invariant.

The weak and electromagnetic amplitudes for the Feynman diagrams in Fig. 1 are described as[6)]

$$\mathcal{M}_Z=\frac{eg_Z^2}{q^2+M_Z^2}(g_V j_\alpha+g_A j_\alpha^5)\langle p(p')|J_\alpha^Z|p(p)\rangle \tag{3}$$

and

$$\mathcal{M}_\gamma=-\frac{e^3}{q^2}j_\alpha\langle p(p')|J_\alpha^{\text{em}}|p(p)\rangle\,, \tag{4}$$

where

$$j_\alpha=\varepsilon_\mu\bar{u}(p_-)\left[\gamma_\mu\frac{1}{i\gamma\cdot(p_--k)+m}\gamma_\alpha+\gamma_\alpha\frac{1}{i\gamma\cdot(k-p_+)+m}\gamma_\mu\right]v(p_+) \tag{5}$$

and

$$j_\alpha^5=\varepsilon_\mu\bar{u}(p_-)\left[\gamma_\mu\frac{1}{i\gamma\cdot(p_--k)+m}\gamma_\alpha\gamma_5+\gamma_\alpha\gamma_5\frac{1}{i\gamma\cdot(k-p_+)+m}\gamma_\mu\right]v(p_+). \tag{6}$$

Here $\varepsilon_\mu$ is the polarization vector of the incident photon, $m$ and $M_Z$ are the masses of the lepton and the weak neutral vector boson $Z$, respectively, and $q=p'-p$ is the momentum transfer.

The matrix elements of the hadronic currents between proton states can be written in terms of the proton form factors as follows:[10)]

$$\langle p(p')|J_\alpha^Z(0)|p(p)\rangle=\frac{iM}{(2\pi)^3\sqrt{p_0'p_0}}\bar{u}(p')\Big[F_{1,p}^Z(q^2)\gamma_\alpha -\frac{F_{2,p}^Z(q^2)}{2M}\sigma_{\alpha\beta}q_\beta+G_{A,p}^Z(q^2)\gamma_\alpha\gamma_5\Big]u(p) \tag{7}$$

and

$$\langle p(p')|J_\alpha^{\text{em}}(0)|p(p)\rangle=\frac{iM}{(2\pi)^3\sqrt{p_0'p_0}}\bar{u}(p')\Big[F_{1,p}^\gamma(q^2)\gamma_\alpha -\frac{F_{2,p}^\gamma(q^2)}{2M}\sigma_{\alpha\beta}q_\beta\Big]u(p), \tag{8}$$

where $M$ is the proton mass. The superscripts $\gamma$ and $Z$ imply the form factors of the electromagnetic and weak neutral currents, respectively, while the subscript

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$p$ indicates the proton form factors. In Eq. (7), we have omitted the induced pseudoscalar form factor because its contribution is negligible for high energies where the lepton mass can safely be ignored.

The cross section for the process (1) can easily be calculated by the use of Eqs. (3) $\sim$ (8). We are now interested in the angular asymmetry for the lepton produced by circularly polarized photons from unpolarized protons, and we are not concerned with the details of the final states of the proton and antilepton. Then, summing over all final states of the proton and the antilepton and over the lepton polarization, and averaging over the initial proton spin, we obtain the differential cross sections for the exclusive lepton pair production of right- and left-handed photons. The results are

$$\frac{d\sigma^{(+)}}{dE_-d\Omega_-}+\frac{d\sigma^{(-)}}{dE_-d\Omega_-}=\frac{2\alpha^3}{\pi^2}\frac{E_-}{E(k\cdot p_-)}\int d\Omega_+\frac{ME_+}{p_0'(k\cdot p_+)q^4}$$
$$\times\left[S_1\frac{q^2}{4M^2}\{G^\gamma_{M,p}(q^2)\}^2+\frac{S_2}{(1+q^2/4M^2)}\left\{(G^\gamma_{E,p}(q^2))^2+\frac{q^2}{4M^2}(G^\gamma_{M,p}(q^2))^2\right\}\right] \tag{9}$$

and

$$\frac{d\sigma^{(+)}}{dE_-d\Omega_-}-\frac{d\sigma^{(-)}}{dE_-d\Omega_-}=-\frac{\alpha^2 g_Z^2}{\pi^3}\frac{E_-}{E(k\cdot p_-)}\int d\Omega_+\frac{ME_+}{p_0'(k\cdot p_+)q^2(q^2+M_Z^2)}$$
$$\times\left[-g_V A_3 G^\gamma_{M,p}(q^2)G^Z_{A,p}(q^2)+g_A\left\{A_1\frac{q^2}{4M^2}G^\gamma_{M,p}(q^2)G^Z_{M,p}(q^2)\right.\right.$$
$$\left.\left.+\frac{A_2}{(1+q^2/4M^2)}\left(G^\gamma_{E,p}(q^2)G^Z_{E,p}(q^2)+\frac{q^2}{4M^2}G^\gamma_{M,p}(q^2)G^Z_{M,p}(q^2)\right)\right\}\right], \tag{10}$$

where

$$E_+=\frac{M(E_--E)+EE_-(1-\cos\theta_-)}{E_-\{1-\cos\theta_+\cos\theta_--\sin\theta_+\sin\theta_-\cos(\phi_+-\phi_-)\}-E(1-\cos\theta_+)-M}, \tag{11}$$

$$p_0'=M+E-E_+-E_-, \tag{12}$$

$$q^2=2M(E-E_+-E_-). \tag{13}$$

Here, $d\sigma^{(\pm)}$ denote the differential cross sections for the polarized photons with positive and negative helicities $\lambda=\pm1$. $E$ and $E_\pm$ are the lab energies of the incoming photon and the outgoing lepton $l^\pm$, respectively. $\theta_\pm$ and $\phi_\pm$ are, respectively, the polar and azimuthal angles of the final lepton momenta $\boldsymbol{p}_\pm$ with respect

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to the direction of the incident photon beam. These kinematical variables are illustrated in Fig. 3. The factors $S_i$ and $A_i$ are the kinematical functions of these variables in the laboratory system. Their explicit formulas are given by Eqs. (19) $\sim$(23) in the latter paper of Ref. 6). $G_E(q^2)$ and $G_M(q^2)$ are the Sachs electric and magnetic form factors which are respectively defined as[11]

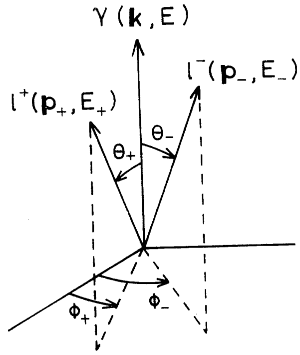


Fig. 3. Kinematical variables in the laboratory system.

$$G_E(q^2)=F_1(q^2)-\frac{q^2}{4M^2}F_2(q^2) \tag{14}$$

and

$$G_M(q^2)=F_1(q^2)+F_2(q^2). \tag{15}$$

We finally note that we have neglected the lepton mass in deriving Eqs. (9) and (10).

From Eqs. (9) and (10), we define the parity-violating asymmetry for the electron (muon) produced by right- and left-handed photons on proton targets:

$$A(p_-;k)=\left[\frac{d\sigma^{(+)}}{dE_-d\Omega_-}-\frac{d\sigma^{(-)}}{dE_-d\Omega_-}\right]\Big/\left[\frac{d\sigma^{(+)}}{dE_-d\Omega_-}+\frac{d\sigma^{(-)}}{dE_-d\Omega_-}\right]. \tag{16}$$

In the following numerical estimate of the asymmetry, we cut off the antilepton energy lower than 1 GeV in practice.

## § 3. Numerical calculations and results

In order to make a numerical calculation of the asymmetry (16), we shall use the Weinberg-Salam model[2] with the Glashow-Iliopoulos-Maiani mechanism.[12] Then, the neutral-current coupling constants in Eq. (2) are given by

$$g_Z=\frac{e}{\sin 2\theta_W},$$

$$g_V=-\frac{1}{2}+2\sin^2\theta_W,$$

$$g_A=-\frac{1}{2}, \tag{17}$$

and the electromagnetic and weak hadronic currents are described in terms of quark fields:

$$J_\mu{}^{\mathrm{em}}=i\frac{2}{3}\bar{u}\gamma_\mu u-i\frac{1}{3}\bar{d}\gamma_\mu d+\cdots, \tag{18}$$

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$$J_\mu^Z = \frac{i}{2}\bar{u}\gamma_\mu(1+\gamma_5)u - \frac{i}{2}\bar{d}\gamma_\mu(1+\gamma_5)d - 2\sin^2\theta_W J_\mu^{\text{em}} + \cdots , \tag{19}$$

where $\theta_{\mathrm{W}}$ is the Weinberg angle and $\cdots$ denotes the strange and charmed quark currents and so on. The mass of the weak neutral vector boson $Z$ is also fixed by the Fermi coupling constant $G_{\mathrm{F}}$ as

$$M_Z^2 = g_Z^2/\sqrt{2}\,G_{\mathrm{F}} . \tag{20}$$

We are now in a position to discuss the form factors for the hadronic currents. By neglecting the contribution of the strange and charmed quarks in the nucleon, the form factors of the neutral vector current can be related to the electromagnetic form factors of nucleons through the isospin property.[7] From Eqs. (18) and (19), we have

$$G^Z_{E,p}(q^2) = \frac{1}{2}[G^\gamma_{E,p}(q^2) - G^\gamma_{E,n}(q^2)] - 2\sin^2\theta_W G^\gamma_{E,p}(q^2),$$

$$G^Z_{M,p}(q^2) = \frac{1}{2}[G^\gamma_{M,p}(q^2) - G^\gamma_{M,n}(q^2)] - 2\sin^2\theta_W G^\gamma_{M,p}(q^2) \tag{21}$$

for the Weinberg-Salam model.[2] The subscript $n(p)$ indicates the neutron (proton) form factors. In a similar manner, we obtain for the neutral axial-vector current[7]

$$G^Z_{A,p}(q^2) = \frac{1}{2}g_A(q^2), \tag{22}$$

where $g_A(q^2)$ is the axial-vector form factor for the neutron $\beta$ decay.

On the other hand, the electromagnetic form factors $G_E^\gamma$ and $G_M^\gamma$ are well known experimentally at least for low energies, and they have the same dipole $q^2$ dependence:

$$G^\gamma_{E,p}(q^2) = \frac{G^\gamma_{M,p}(q^2)}{1+\mu_p} = \frac{G^\gamma_{M,n}(q^2)}{\mu_n} = \left(1+\frac{q^2}{0.71\ \mathrm{GeV}^2}\right)^{-2}, \tag{23}$$

$$G^\gamma_{E,n}(q^2) \approx 0 ,$$

where $\mu_p = 1.79$ and $\mu_n = -1.91$ are the proton and neutron anomalous magnetic moments, respectively.[8] Similarly, we take the axial-vector form factor to be of the dipole form

$$g_A(q^2) = g_A(0)\left(1+\frac{q^2}{M_A{}^2}\right)^{-2}, \tag{24}$$

where $g_A(0) = 1.253 \pm 0.007$ is the axial-vector coupling constant for the neutron $\beta$ decay.[13] The parameter $M_A$ is experimentally determined by the pseudo-elastic

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neutrino reactions,[9] but it is not so well settled yet. In our numerical calculations, we take $M_A^2=0.90\,\mathrm{GeV}^2$. It is, however, to be noted that our numerical results for the asymmetries are scarcely affected by the value of $M_A^2$ so far as it ranges from $0.71\,\mathrm{GeV}^2$ to $1.10\,\mathrm{GeV}^2$, compatible with the experiments.[9]

We shall present the numerical results of the asymmetry in the following configurations:

(i) $E=10\,\mathrm{GeV}$, $\theta_-=1^\circ$, $5^\circ$,

(ii) $E=20\,\mathrm{GeV}$, $\theta_-=1^\circ$, $5^\circ$, $10^\circ$,

(iii) $E=50\,\mathrm{GeV}$, $\theta_-=5^\circ$, $10^\circ$.

In Figs. 4~8, the asymmetry is shown as a function of the outgoing lepton energy $E_-$ for the Weinberg-Salam model. In these numerical calculations, we have used $\sin^2\theta_\mathrm{W}=0.23$ for the Weinberg angle which is quite consistent with all the experimental data.[14] In the case of the incident photon energy, $E=10\,\mathrm{GeV}$, we find the parity-violating asymmetries to be of order $10^{-9}$ and $10^{-7}$ for the lepton production angle $\theta_-=1^\circ$ and $5^\circ$. For $E=20\,\mathrm{GeV}$, the asymmetries are of order $10^{-7}$, $10^{-6}$ and $10^{-5}$ for $\theta_-=1^\circ$, $5^\circ$ and $10^\circ$, respectively, while for $E=50\,\mathrm{GeV}$, they are of order $10^{-5}$ and $10^{-4}$ for $\theta_-=5^\circ$ and $10^\circ$ respectively. It is to be noted that the difference of the order of the above asymmetries is mainly due to the kinematical factor, namely, the momentum transfer squared $q^2$.

We shall make further remarks on our numerical results. For the Weinberg-Salam model with $\sin^2\theta_\mathrm{W}=0.23$, we have $g_V=-0.04$ and $g_A=-0.5$ from Eq. (17). Consequently, the numerical values of the asymmetry in Figs. 4~8 are practically given by the $g_A$-dependent terms in Eq. (10). In contrast, we also show in Fig. 9 the asymmetry for the hybrid model*) with the same Weinberg angle which gives $g_V=-0.54$ and $g_A=0$. In this case, the asymmetry comes from only the $g_V$-dependent term in Eq. (10). Comparing Fig. 7 with Fig. 9, we find that the asymmetry for the Weinberg-Salam model is about four or five times as large as that for the hybrid model.*) This fact also means a small dependence of the asymmetry upon $\sin^2\theta_\mathrm{W}$ for the Weinberg-Salam model. The above-mentioned feature will do for distinguishing between the two models.

The parity-violating effects clearly increase with the angle $\theta_-$ of the observed lepton. However, the differential cross section for the photoproduction of lepton pairs exponentially damps with this angle and also with the lepton energy $E_-$. In Fig. 10, for example, we illustrate it as a function of $E_-$ for the fixed angles $\theta_-=1^\circ$, $5^\circ$ and $10^\circ$ in the case $E=20\,\mathrm{GeV}$. Thus, there is no advantage in setting the angle $\theta_-$ to be so large in the experiment.

In the above numerical estimates, we have cut off the antilepton energy lower than 1 GeV, as was previously mentioned. In fact, this cutoff may be removed,

*) The right-handed electron (or muon) is in a doublet but the right-handed quarks in singlets.

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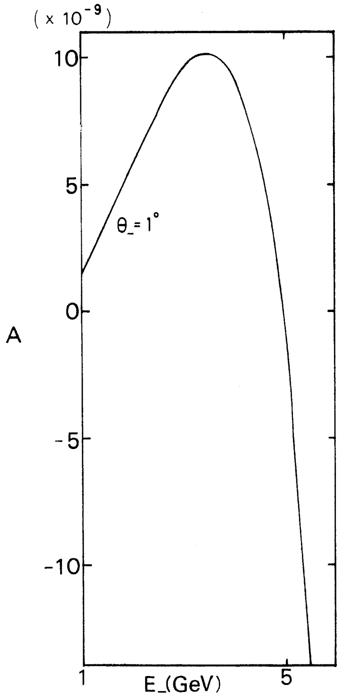


Fig. 4. The asymmetry $A$ as a function of $E_-$ for $\theta_-=1°$ and $E=10$ GeV in the Weinberg-Salam model with $\sin^2\theta_W=0.23$.

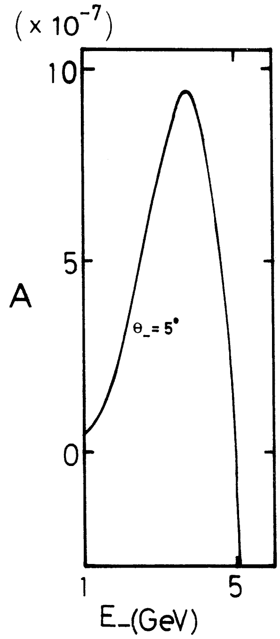


Fig. 5. The asymmetry $A$ as a function of $E_-$ for $\theta_-=5°$ and $E=10$ GeV in the Weinberg-Salam model with $\sin^2\theta_W=0.23$.

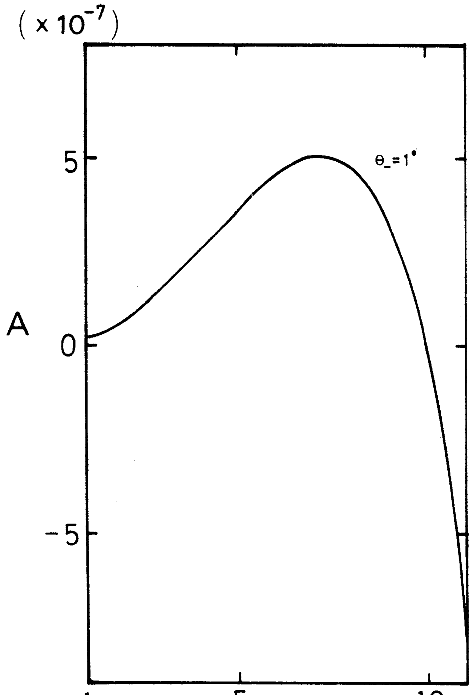


Fig. 6. The asymmetry $A$ as a function of $E_-$ for $\theta_-=1°$ and $E=20$ GeV in the Weinberg-Salam model with $\sin^2\theta_W=0.23$.

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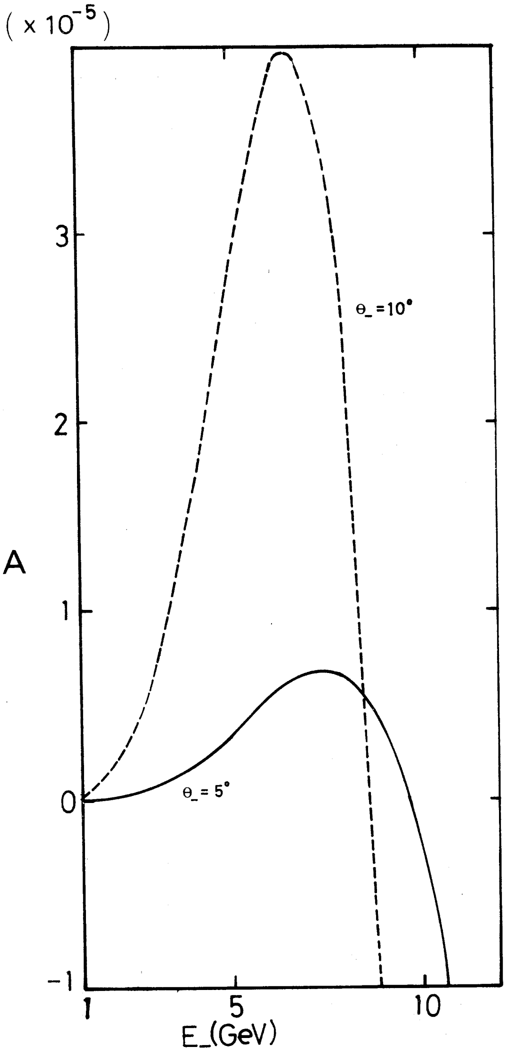


Fig. 7. The asymmetry $A$ as a function of $E_-$ for $\theta_-=5°$, $10°$ and $E=20$ GeV in the Weinberg-Salam model with $\sin^2\theta_W=0.23$. The solid and dashed curves correspond to $\theta_-=5°$ and $10°$, respectively.

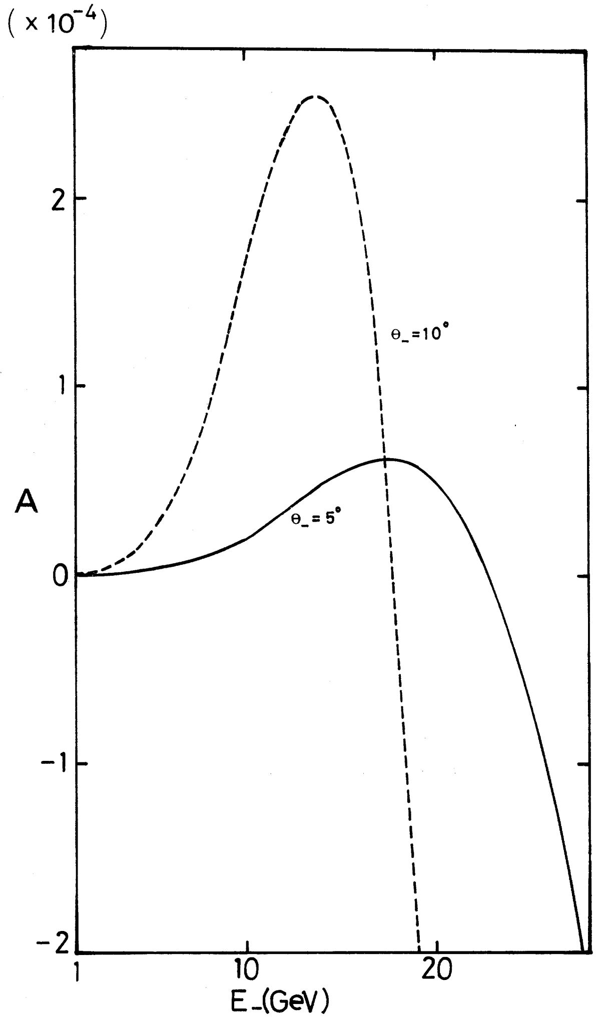


Fig. 8. The asymmetry $A$ as a function of $E_-$ for $\theta_-=5°$, $10°$ and $E=50$ GeV in the Weinberg-Salam model with $\sin^2\theta_W=0.23$. The solid and dashed curves correspond to $\theta_-=5°$ and $10°$, respectively.

because it makes no visible difference in our numerical results as far as they are shown in Figs. 4∼10. Of course, it does affect the behavior near the maximum energy of the lepton.

In conclusion, we shall briefly remark the feasibility of observing the above neutral-current effects. The monochromatic and polarized photon beam of 20 GeV will be available at SLAC.[15] So it is expected to be feasible to measure the

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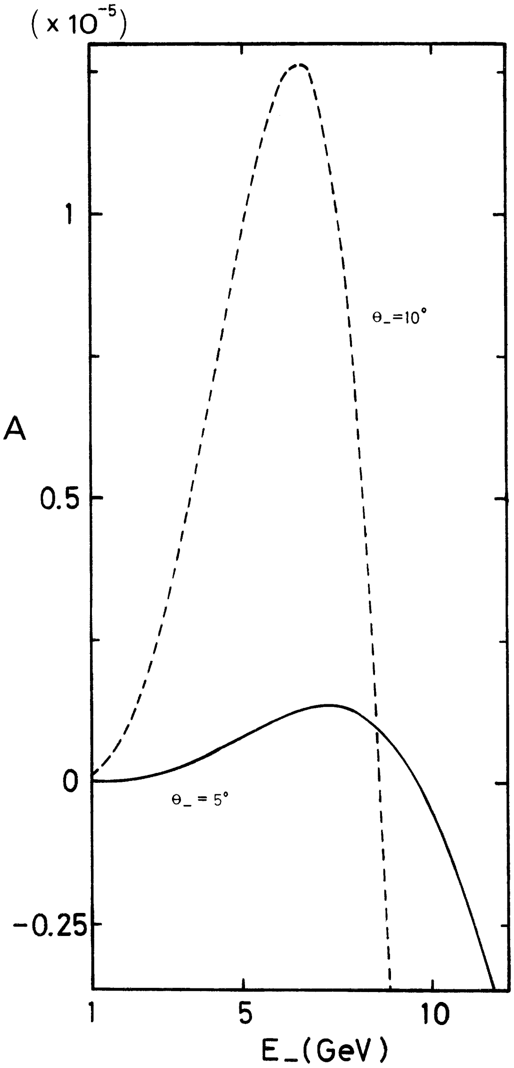


Fig. 9. The asymmetry for the hybrid model with $\sin^2\theta_W = 0.23$ and $E = 20$ GeV. The notation is the same as in Fig. 7.

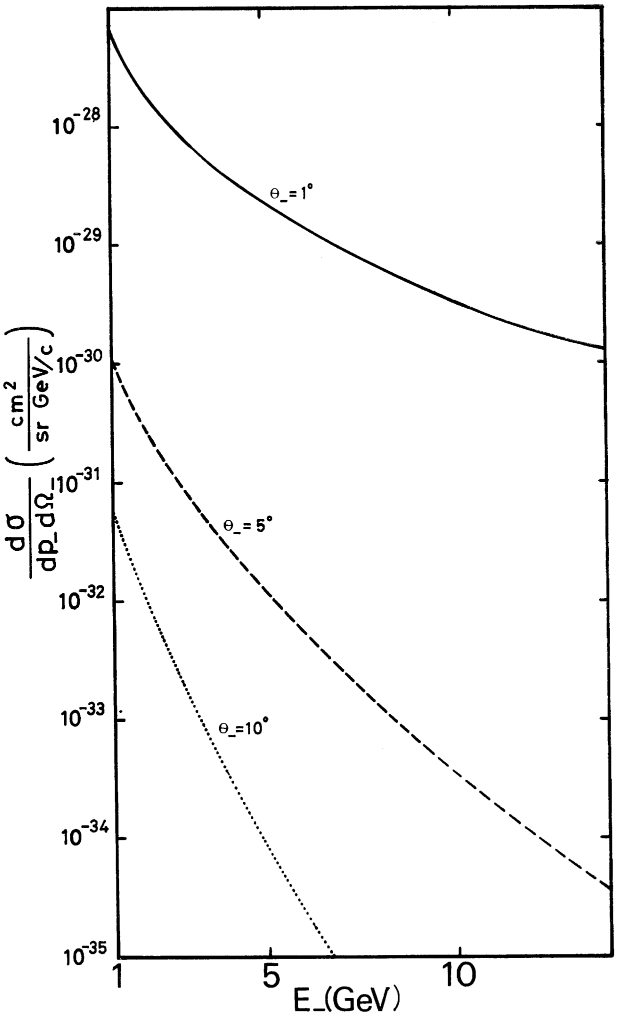


Fig. 10. The differential cross section, $d\sigma/dE_- d\Omega_- = (d\sigma^{(+)} + d\sigma^{(-)})/2dE_- d\Omega_-$, for the lepton pair production with unpolarized photons. It is shown as a function of the lepton energy $E_-$ for the fixed angle at the incident photon energy of 20 GeV. The solid, dashed and dotted curves correspond to $\theta_- = 1°$, 5° and 10°, respectively.

parity-violating asymmetry in the exclusive photoproduction of lepton pairs. Such a measurement is very useful for the determination of the electron-quark and muon-quark neutral-current couplings.

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