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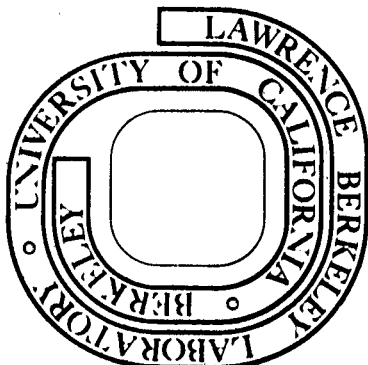
Richard Simard and Mahiko Suzuki

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μe Events in Electron-Positron Annihilation
with Longitudinally Polarized Beams

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Muon-electron production processes are examined in the case where one of electron-positron beams is longitudinally polarized. A special emphasis is put on the asymmetry in the angular distribution of muon (or electron) emission to reveal the structure of weak interactions of possible heavy leptons. The angular asymmetry will easily distinguish between $V - A$ and $V + A$ for the weak current of heavy leptons.

July 15, 1976

I. Introduction

The μe events discovered at SPEAR¹ indicate existence of heavy leptons. Details of their decay properties are of special interest from the viewpoint of weak interaction theory. At the present moment little is known about their identity beyond the fact that they decay into a muon or an electron through three-body decay. The distributions of the collinearity angle and the momenta of μe are insensitive to the weak current of the heavy leptons being $V - A$ or $V + A$.²⁻⁵ It is rather difficult to distinguish between $V - A$ and $V + A$ through the collinearity angle and the momentum spectra.

Meanwhile, large transverse polarizations have been obtained at SPEAR in the vicinity of $\sqrt{s} = 7.4$ GeV. It is expected to obtain large polarizations more easily at PEP and PETRA.⁶ Since transverse polarizations are not very useful for the purpose of exploring weak interactions, or parity violation,⁷ it is desired to rotate one or both of the beam polarizations into the longitudinal direction.⁸ The parallel longitudinal polarizations would be most appropriate for our purpose, but it is almost equally useful if one of the beams is polarized longitudinally and the other beam remains unpolarized or transversely polarized. We examine in this paper the angular distributions of muons and electrons in the μe events when one of the initial beams is polarized longitudinally. With the initial beam polarized longitudinally, properties associated with parity will manifest themselves clearly, for instance, in the asymmetry of the angular distribution. This asymmetry in the emission angles of muons and electrons is large enough to distinguish easily between $V - A$ and $V + A$ for the heavy lepton currents.

II. Angular distribution of μe events.

The distributions of the colinearity angle and the momenta have been calculated by many people,²⁻⁵ but they can reveal little of the structure of weak interactions. Being interested in parity violation effects in heavy lepton decays, we calculate here the asymmetry in the $\cos\theta$ distribution of muons and electrons in the final states of the μe events. (Figure 1.) The same asymmetry in inclusive muon (electron) production might serve our purpose, but it would be largely contaminated by the muons (electrons) due to charmed hadrons or other heavy hadrons stable against strong and electromagnetic decays. To make sure that final light leptons originate from heavy leptons, one should select out the μe events with no accompanying hadrons.

The interaction for heavy lepton decay is written in the Fierz-transformed four-fermion form as

$$\begin{aligned}
 L_{\text{int}} = & (\bar{\psi}_\ell \psi_L) \{ \bar{\psi}_{\nu L} (C_S + C_S' \gamma_5) \psi_{\nu \ell} \} \\
 & + (\bar{\psi} \gamma_\lambda \psi_L) \{ \bar{\psi}_{\nu L} \gamma^\lambda (C_V + C_V' \gamma_5) \psi_{\nu \ell} \} \\
 & + \frac{1}{2} (\bar{\psi}_\ell \sigma_{\lambda\kappa} \psi_L) \{ \bar{\psi}_{\nu L} \sigma^{\lambda\kappa} (C_T + C_T' \gamma_5) \psi_{\nu \ell} \} \\
 & + (\bar{\psi}_\ell \gamma_\lambda \gamma_5 \psi_L) \{ \bar{\psi}_{\nu L} \gamma^\lambda \gamma_5 (C_A + C_A' \gamma_5) \psi_{\nu \ell} \} \\
 & + (\bar{\psi}_\ell \gamma_5 \psi_L) \{ \bar{\psi}_{\nu L} \gamma_5 (C_P + C_P' \gamma_5) \psi_{\nu \ell} \},
 \end{aligned} \tag{2.1}$$

where ψ_ℓ and $\psi_{\nu \ell}$ are Dirac fields of a light lepton (μ or e) and its neutrino, ψ_L and $\psi_{\nu L}$ are Dirac fields of a heavy lepton and its neutrino, and the convention of the γ matrices and the metric tensor is the one that

is found in Reference 9. As is usual,¹⁰ we define

$$\begin{aligned}
 a &= |c_S|^2 + |c'_S|^2 + |c_P|^2 + |c'_P|^2, \\
 b &= |c_V|^2 + |c'_V|^2 + |c_A|^2 + |c'_A|^2, \\
 c &= |c_T|^2 + |c'_T|^2, \\
 \bar{\alpha} &= |c_S|^2 + |c'_S|^2 - |c_P|^2 - |c'_P|^2, \\
 \bar{\beta} &= |c_V|^2 + |c'_V|^2 - |c_A|^2 - |c'_A|^2, \\
 a' &= -(c_S c_P'^* + c'_S c_P^* + c_S^* c_P' + c_S'^* c_P), \\
 b' &= c_V c_A'^* + c'_V c_A^* + c_V^* c_A' + c_V'^* c_A, \\
 c' &= -(c_T c_T'^* + c_T^* c_T'), \\
 \bar{\alpha}' &= -(c_S c_P'^* + c'_S c_P^* - c_S^* c_P' - c_S'^* c_P), \\
 \bar{\beta}' &= c_V c_A'^* + c'_V c_A^* - c_V^* c_A' - c_V'^* c_A,
 \end{aligned} \tag{2.2}$$

and also

$$\begin{aligned}
 A_0 &= a + 4b + 6c, \\
 \rho &= (3b + 6c)/A_0, \\
 \eta &= (\bar{\alpha} - 2\bar{\beta})/A_0, \\
 \xi &= (-3a' - 4b' + 14c')/A_0, \\
 \delta &= (3b' - 6c')/(A_0 \xi).
 \end{aligned} \tag{2.3}$$

If the heavy lepton current is of $V - A$ prior to the Fierz transform, one finds that $\rho = \delta = 3/4$ and $\xi = 1$. If it is of $V + A$, one finds that $\rho = \delta = 0$ and $\xi = 3$. In either case, $\eta = 0$. In the present paper the mass of the neutrino associated with the heavy lepton is assumed to be zero.

Let us first calculate for the process in which the electron beam is polarized longitudinally along its own momentum (as a vector) with the positron beam transversely polarized. We consider the angular distribution of light leptons of negative charge in the final states of such a process. (Figure 2). The other cases are obtained trivially from this case. Only the one-photon annihilation is taken into account. In computing the differential cross section we follow the method of Tsai² modified to a manifestly covariant form.

The L^+L^- production cross section with L^+L^- polarized arbitrarily is given in the e^+e^- laboratory frame by

$$\frac{d\sigma}{d\Omega_L} = \frac{\alpha^2 \beta}{(q^2)^3} W, \quad (2.4)$$

$$W = W_1 + \mathcal{P} W_2 + O(m_e^2), \quad (2.5)$$

$$\begin{aligned} W_1 = & 2 \left\{ (Pk)(P'k') + (Pk')(P'k) + \frac{1}{2} q^2 M^2 \right\} \left\{ 1 - (ss') \right\} \\ & - q^2 (sP')(s'P) + \frac{1}{2} (q^2)^2 (ss') - q^2 \left\{ (sk)(s'k') + (sk')(s'k) \right\} \\ & + 2(sP') \left\{ (Pk)(s'k') + (Pk')(s'k) \right\} \\ & + 2(s'P) \left\{ (P'k)(sk') + (P'k')(sk) \right\}, \end{aligned} \quad (2.6)$$

$$W_2 = -Mq^2 \left\{ (sk) + (s'k) - (sk') - (s'k') \right\}, \quad (2.7)$$

where

$$\begin{aligned}
 \mathcal{P} & ; \text{ magnitude of } e^+e^- \text{ beam polarizations,} \\
 s_\mu(s'_\mu) & ; \text{ four-vector polarization of } L^- (L^+), \\
 M & ; \text{ mass of } L^\pm, \\
 P_\mu(P'_\mu) & ; \text{ four-momentum of } L^-(L^+), \\
 k_\mu(k'_\mu) & ; \text{ four-momentum of initial } e^-(e^+), \\
 \beta & = |\underline{P}|/P_0, \text{ and } q = k + k'.
 \end{aligned} \tag{2.8}$$

The differential decay rate of $L^\pm$ is given by

$$P_0 \frac{d\Gamma^-}{d^3p} = A^- + (\text{sp}) B^- , \tag{2.9}$$

for L^- and a similar expression for L^+ with A^- and B^- replaced by A^+ and B^+ . Here p is the four-momentum of the light lepton. In the approximation of ignoring the square of the light lepton mass, the invariant decay amplitudes $A^\pm$ and $B^\pm$ are given by

$$A^\pm = \frac{A_0 M}{96\pi^4 P_0} y \left\{ 3 \left(\frac{M}{2} - \frac{y}{M} \right) + 2\rho \left(\frac{4y}{3M} - \frac{M}{2} \right) + \frac{3mM}{y} \gamma \left(\frac{M}{2} - \frac{y}{M} \right) \right\}, \tag{2.10}$$

$$B^\pm = \mp \frac{A_0 M^2}{96\pi^4 P_0} \xi \left\{ \left(\frac{M}{2} - \frac{y}{M} \right) + 2\delta \left(\frac{4y}{3M} - \frac{M}{2} \right) \right\}, \tag{2.11}$$

where $y = (pP)$.

The final phase volume is fully integrated over L^+ , so that the s' dependent terms in (2.4) - (2.7) do not contribute to the differential

production cross section $p_0(d\sigma/d^3p)$. The spin dependence of L^- in $d\sigma/d\Omega_L$ and $p_0(d\Gamma^-/d^3p)$ is correctly included by putting them together as

$$p_0 \frac{d\sigma}{d\Omega_L d^3p} = \frac{\alpha^2 \beta r^2}{(q^2)^3 \Gamma} \left\{ \tilde{W}_1 A^- - (\tilde{p} \tilde{W}_2) B^- \right\}, \quad (2.12)$$

where $\tilde{W}_1$ and $\tilde{W}_2^\mu$ are defined as

$$\frac{d\sigma}{d\Omega_L} = \frac{\alpha^2 \beta}{(q^2)^3} \left\{ \tilde{W}_1 + (s_\mu \tilde{W}_2^\mu) + (s'_\mu \tilde{W}_3^\mu) + (s_\mu s'_\nu \tilde{W}_4^{\mu\nu}) \right\}, \quad (2.13)$$

where r is the branching ratio of $L^\pm$ into $l^\pm + \nu_l(\bar{\nu}_l) + \bar{\nu}_L(\nu_L)$, Γ is the decay rate in the e^+e^- laboratory frame of $L \rightarrow l + \nu_l + \nu_L$, integrated over the entire phase volume, and $\tilde{p}$ is defined by

$$\tilde{p}_\mu = p_\mu - P_\mu(pP)/M^2. \quad (2.14)$$

Equation (2.12) is integrated over $d\Omega_L$ with $\underline{p}$ kept fixed. Measuring the solid angle of $\underline{p}$ with respect to $\underline{p}$, one can integrate over the azimuthal angle Φ . The polar angle Θ should be replaced by a new variable $y = (pP) = pP_0(1 - \beta \cos\Theta) + O(m^2)$. The region of integral over y is restricted by $|\cos\Theta| \leq 1$ and $0 \leq (P - p)^2 \leq (M - m)^2$ to

$$\text{Max}(mM, \frac{xM^2}{1+\beta}) \leq y \leq \text{Min}(\frac{1}{2}M^2, \frac{xM^2}{1-\beta}) \quad (2.15)$$

up to $O(m^2)$. We thus obtain

$$\frac{d\sigma}{dx d\cos\theta} = \frac{16\pi\alpha^2 r^2}{q^2(1+m\eta/M)} \left\{ (1+\cos^2\theta)G_1(x) + \left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right)G_2(x) - 2\xi P \cos\theta G_3(x) \right\}, \quad (2.16)$$

where $x = |\underline{p}|/k_0$, $\gamma = P_0/M$, θ is the emission angle of the light lepton l^- measured from the direction of the electron beam momentum $\underline{k}$, and

$$G_1(x) = \left(1 + \frac{1}{2\gamma^2}\right) \left[\left\{ \frac{3}{16} f_2(x) - \frac{1}{8} f_3(x) \right\} + \rho \left\{ -\frac{1}{8} f_2(x) + \frac{1}{9} f_3(x) \right\} \right. \\ \left. + \frac{m^2}{M} \gamma \left\{ \frac{3}{4} f_1(x) - \frac{3}{8} f_2(x) \right\} \right], \quad (2.17)$$

$$G_2(x) = \frac{1}{x\gamma^2} \left[\left\{ -\frac{1}{8} f_3(x) + \frac{3}{32} f_4(x) \right\} + \frac{3}{x\gamma^2} \left\{ \frac{1}{128} f_4(x) - \frac{1}{160} f_5(x) \right\} \right. \\ \left. + \rho \left\{ \frac{1}{12} f_3(x) - \frac{1}{12} f_4(x) \right\} + \frac{\rho}{x\gamma^2} \left\{ -\frac{1}{64} f_4(x) + \frac{1}{60} f_5(x) \right\} \right. \\ \left. + \frac{m^2}{M} \left\{ -\frac{3}{8} f_2(x) + \frac{1}{4} f_3(x) \right\} + \frac{m^2}{Mx\gamma^2} \left\{ \frac{1}{16} f_3(x) - \frac{3}{64} f_4(x) \right\} \right]. \quad (2.18)$$

$$G_3(x) = x \left\{ \frac{1}{4} f_1(x) - \frac{1}{8} f_2(x) \right\} + \delta x \left\{ -\frac{1}{2} f_1(x) + \frac{1}{3} f_2(x) \right\} \\ + \left\{ -\frac{1}{16} f_2(x) + \frac{1}{24} f_3(x) \right\} + \frac{1}{x\gamma^2} \left\{ \frac{1}{48} f_3(x) - \frac{1}{64} f_4(x) \right\} \\ + \delta \left\{ \frac{1}{8} f_2(x) - \frac{1}{9} f_3(x) \right\} + \frac{\delta}{x\gamma^2} \left\{ -\frac{1}{24} f_3(x) + \frac{1}{24} f_4(x) \right\}, \quad (2.19)$$

$$f_n(x) = \left(\frac{2}{M^2} \right)^n \left\{ y_{\max}^n(x) - y_{\min}^n(x) \right\}. \quad (2.20)$$

In Equation (2.20), $y_{\max}(x)$ and $y_{\min}(x)$ stand for the upper and lower limits of integral as given in (2.15).

We write the production cross section of light leptons in the form of

$$\frac{d\sigma}{dx d\cos\theta} = r^2 \sigma_{\text{tot}}(e^+e^- \rightarrow \mu^+ \mu^-) R(x; \cos^2\theta) \left\{ 1 + \alpha(x; \cos^2\theta) \rho \cos\theta \right\}. \quad (2.21)$$

The integral of $R(x; \cos^2\theta)$ in $\cos\theta$ and x over the entire range of physical region tends to unity as $\gamma \rightarrow \infty$, thus leading to $\sigma_{\text{tot}}(e^+e^- \rightarrow L^+L^-) \longrightarrow \sigma_{\text{tot}}(e^+e^- \rightarrow \mu^+\mu^-)$.

If one measures the emission angle of ℓ^+ instead of ℓ^- in the process under consideration, one should replace the polarization $\mathcal{P}$ by $-\mathcal{P}$. The same switch of sign should be done when ℓ^- is measured in the annihilation of a transversely polarized electron beam with a positron beam polarized longitudinally along the positron beam momentum (opposite to the electron beam momentum). The formula (2.21) is valid in the case that ℓ^+ is measured in the annihilation of a transversely polarized electron beam and a positron beam polarized along its own momentum.

III. Numerical estimate.

A numerical estimate has been done for the magnitude of cross section in terms of $R(x; \cos^2\theta)$ and for the asymmetry $\alpha(x; \cos^2\theta)$. Both of these quantities are dependent on the velocity of L^+ . We have plotted here the results for the $V - A$ and $V + A$ currents provided that $(\ell\gamma)$ current is always of $V - A$. For $M \gtrsim 2.0$ GeV, $R(x; \cos^2\theta)$ and $\alpha(x; \cos^2\theta)$ are insensitive to the light lepton mass even near $x = 0$, so we have drawn the curves for $m = m_e \approx 0$. General behaviors of R and α are rather insensitive to values of γ as long as γ is larger than three or so. Unlike the collinearity angle or the momentum spectra in the annihilation of unpolarized or transversely polarized beams, the asymmetry α will distinguish $V - A$ and $V + A$ clearly. The magnitude of the asymmetry tends to unity at $\cos\theta = \pm 1$ and $x = 1$ as $\gamma \rightarrow \infty$, as is expected from helicity conservation. The magnitude of cross section approaches zero as $x \rightarrow 1$ since L^+ decay into three bodies. To obtain the maximum efficiency, one should choose the region of

$$0.4 \lesssim x \lesssim 0.6$$

(3.1)

or possibly

$$x \lesssim 0.05, \quad (3.2)$$

and stay in the forward-backward cones of, say,

$$|\cos\theta| \lesssim 0.5. \quad (3.3)$$

In Figure 3 are plotted the cross section in terms of the quantity $R(x; \cos^2\theta)$ and the asymmetry $\alpha(x; \cos^2\theta)$, both defined in (2.21), as functions of $x = |\underline{p}|/k_0$ at $\gamma = 2, 6$, and 10 . The $\cos\theta$ dependence of α has been shown in Figure 4. Finally, fixing values of x at 0.5 and 0.05 , we have plotted the γ dependence of α between $\gamma = 2$ and $\gamma = 10$ in Figure 5.

IV. Comment.

Semileptonic decays of charmed hadrons or other heavy hadrons stable against strong and electromagnetic interactions can produce μe events, but the criterion of selecting the μe events with no accompanying hadron, charged or neutral (except for K_L^0), in final states eliminates all but $e^+e^- \rightarrow D^+D^- (F^+F^-) \rightarrow \mu + e + \nu_\mu + \nu_e$. If stable D^+ and F^+ are of $J^P = 0^-$ as the ψ spectroscopy suggests, the branching ratio into $(l\nu_l)$ is negligibly small in the $V \pm A$ interactions. If D^+ and F^+ of $J^P = 1^-$ should decay through weak interactions, one might have to separate them out. But, strong damping of form factors will suppress two-body hadronic channels so severely that we would hardly worry about this possibility. Because of this reason we have proposed here to examine only the μe events rather than inclusive μ (or e) production.

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- * Research supported by Energy Research and Development Administration.
- ** Research supported by National Science Foundation under Grant Number PHY 74-08174-A02 and in part by Energy Research and Development Administration.
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Figure Captions

- Figure 1. A μe event with an electron beam polarized longitudinally.
- Figure 2. Kinematics of μe events in the e^+e^- laboratory frame.
- Figure 3. Production cross section in terms of $R(x; \cos^2\theta)$ and asymmetry parameter $\alpha(x; \cos^2\theta)$ as functions of $x = |\underline{p}|/k_0$ at $\cos\theta = 1$. See Equation (2.21) in the text for the definitions of $R(x; \cos^2\theta)$ and $\alpha(x; \cos^2\theta)$.
- Figure 4. Asymmetry parameter $\alpha(x; \cos^2\theta)$ as a function of $\cos\theta$ at $x = 0.5$ and $x = 0.05$. The value of γ is equal to 10 in the both cases.
- Figure 5. Dependence on γ of asymmetry parameter $\alpha(x; \cos^2\theta)$ at $x = 0.5$ and $x = 0.05$. The top two curves are those for $x = 0.05$ and the two bottom curves are those for $x = 0.5$. The value of θ is equal to 0° in the both cases.

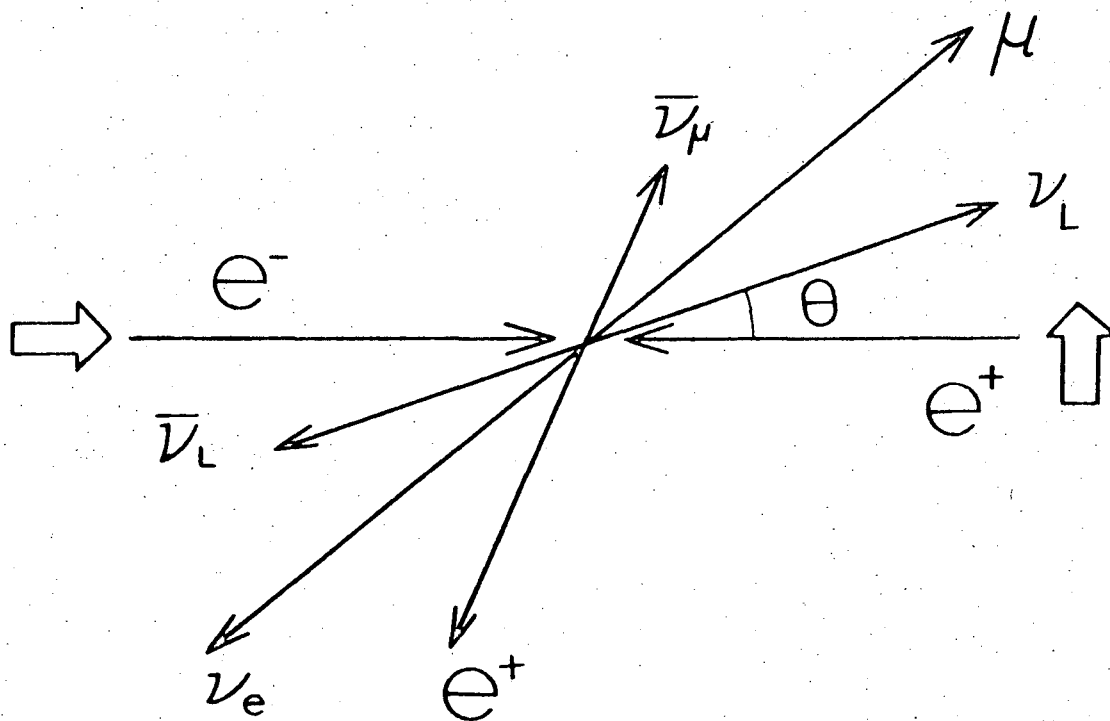


Figure 1.

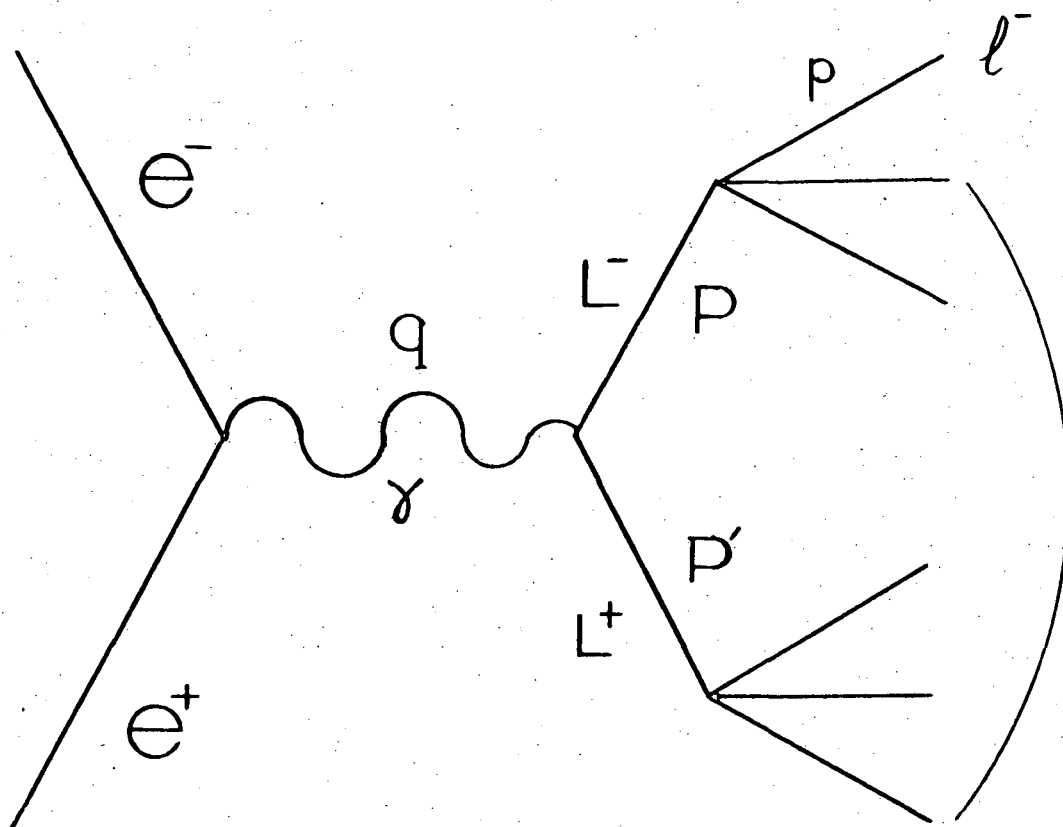


Figure 2.

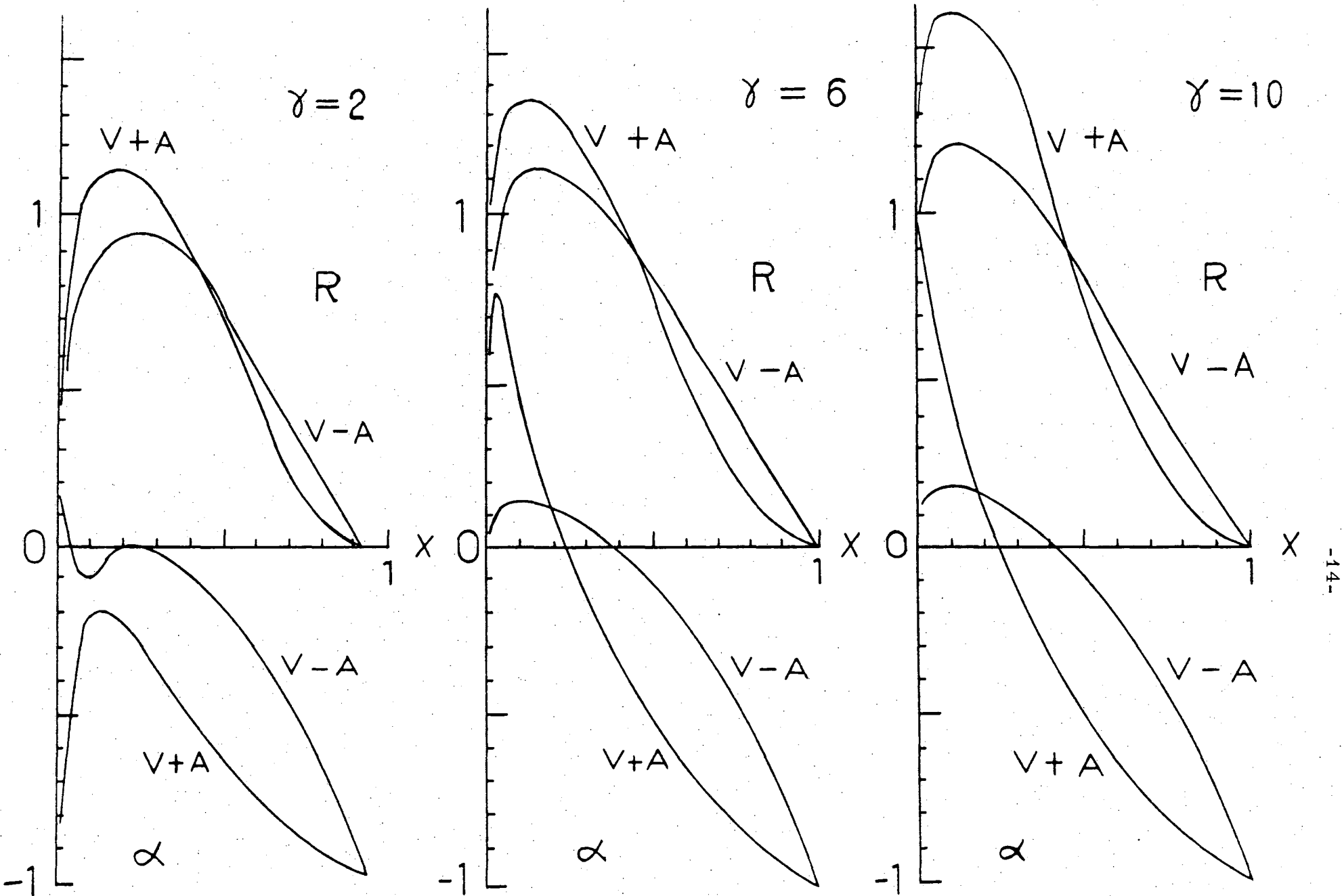


Figure 3.

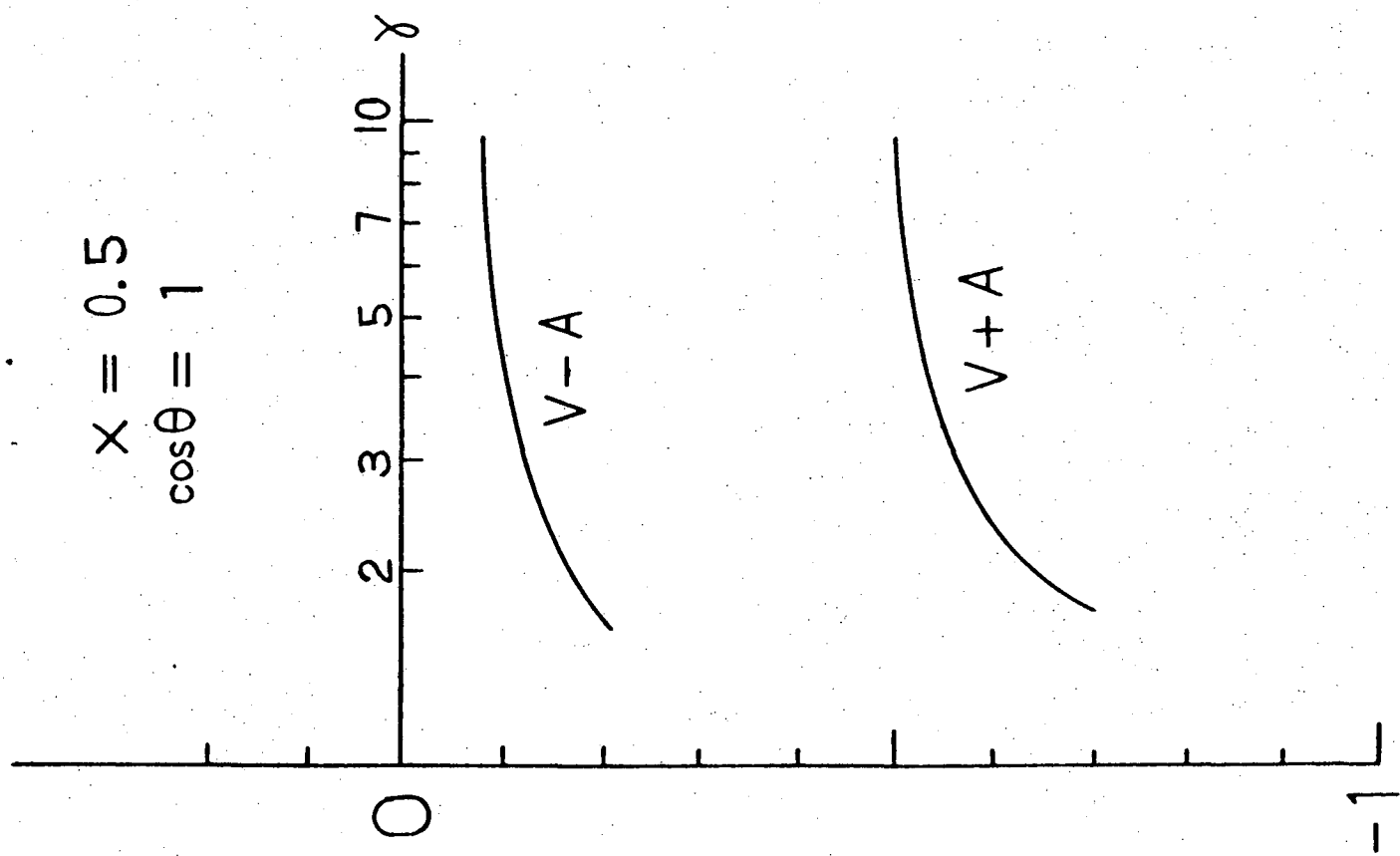
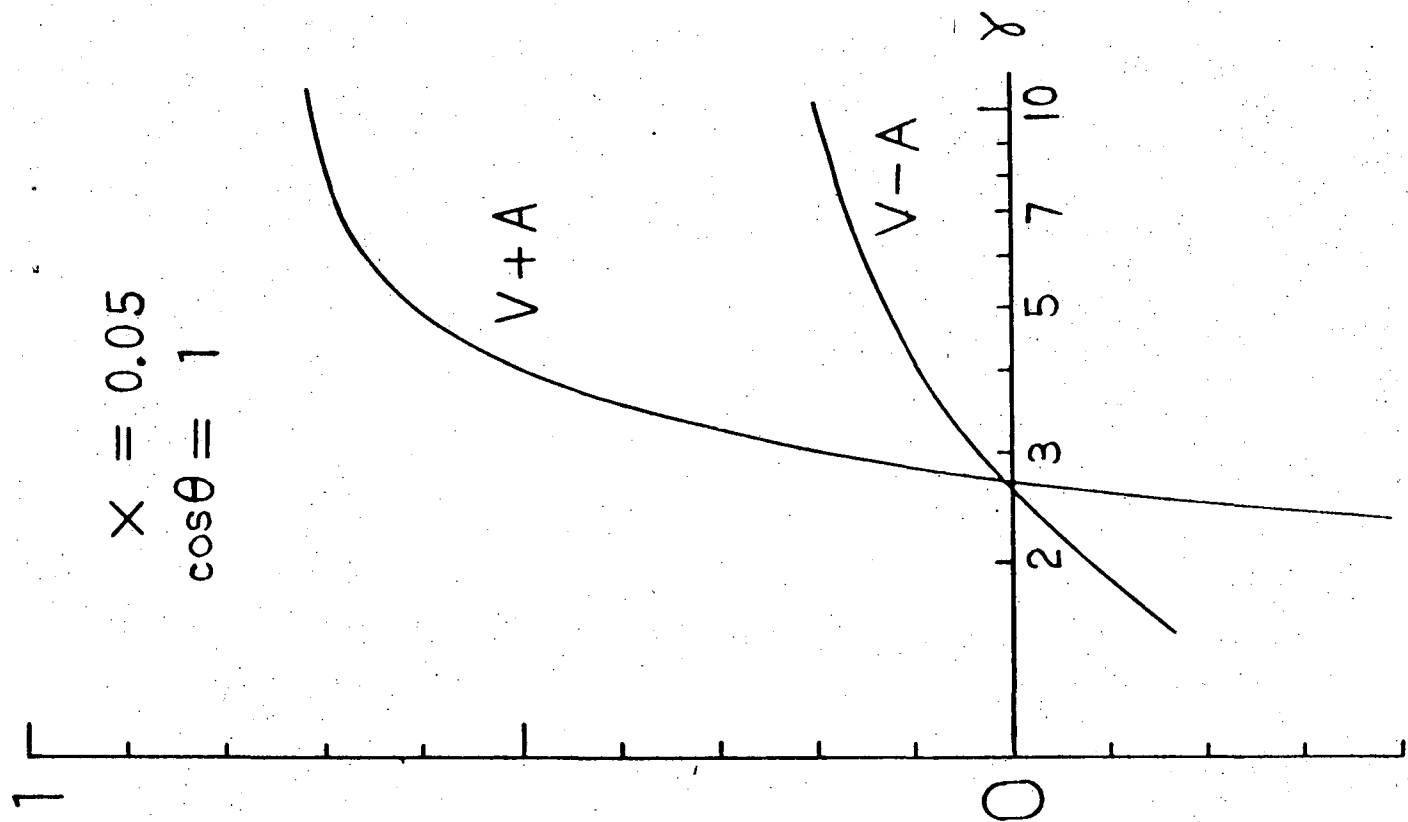


Figure 4.

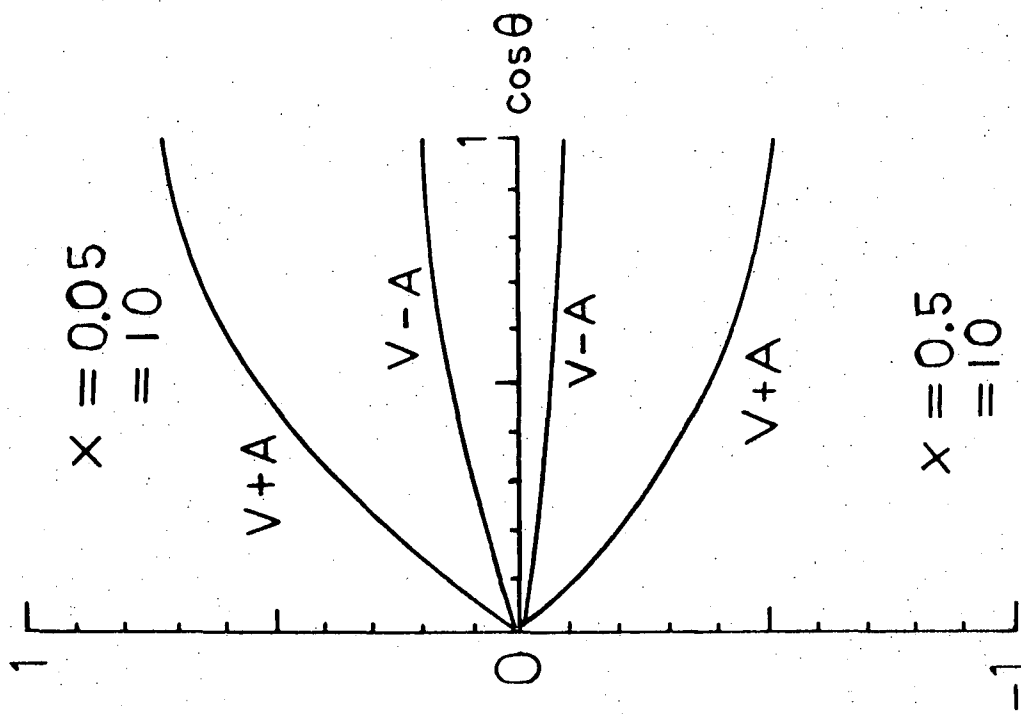


Figure 5.

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