Test for chirality of heavy-lepton current in inclusive pion production by electron-positron annihilation

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Parity mixing in the weak current of charged heavy leptons causes a conspicuous forward-backward asymmetry in the cosθ distribution of inclusive hadron spectra near the high-energy end, when one of the initial electron-positron beams is longitudinally polarized. The asymmetry is estimated for vector and axial-vector currents at PEP and PETRA energies. It is quite easy to distinguish experimentally between $V-A$ and $V+A$ provided that the decay branching ratio $L^{\pm}$ into $L \to \nu_L + \pi$ is not too far from the value predicted by universality ($\sim$ 10%).

I. INTRODUCTION

The discovery of the μe events at SPEAR[1] has prompted numerous theoretical studies on heavy leptons; in particular, energy and angular distributions of secondary light leptons and hadrons.[2,3] It is, however, rather difficult to determine the chiral property of the weak current that causes heavy lepton decays. Having in mind that longitudinal polarizations will be available at the PEP colliding-beam machine,[4] we present here a clear test to determine the chiral property of the weak heavy-lepton current. It consists of measuring charged pions (and kaons) of very high energy produced through $L \to \nu_L + \pi(K)$.

II. ANGULAR DISTRIBUTION

The angular distribution of pions in the one-photon annihilation

$$e^- + e^+ \xrightarrow[``\gamma"]{} L^- + L^+, \quad L^+ \to \text{anything}, \quad L^- \to \nu_L + \pi^- \tag{2.1}$$

and a similar process is calculated in the center-of-mass frame of e^+e^- when one of the e^+e^- beams is longitudinally polarized. The reasons why this particular decay mode is chosen are that the decay matrix element is calculable accurately when universality holds, and that because the decay is a two-body decay the pion spectrum extends to the high-energy end of the x distribution. Let the semileptonic weak interaction of $L^{\pm}$ be

$$H_{\text{int}} = (\tfrac{1}{2})^{1/2} G[\nu_L \gamma_\mu (1 + g_a \gamma_5) L] J^\mu + \text{H.c.}, \tag{2.2}$$

$$J^\mu = \bar{\mathfrak{N}} \gamma^\mu (1-\gamma_5) \mathcal{P} \cos\theta_C + \bar{\lambda} \gamma^\mu (1-\gamma_5) \mathcal{P} \sin\theta_C, \tag{2.3}$$

where θ_C is the Cabibbo angle. Above several GeV in the center-of-mass energy, electron-positron beams are highly polarized transversely, and it is possible to rotate one or both of the polarizations into the longitudinal direction at the PEP and the PETRA.[4] For the purpose of producing an asymmetry in the angular distribution we consider first the configuration in which the electron beam is polarized longitudinally along the direction of its own momentum and the positron beam remains polarized transversely. The differential cross section of the pions emerging from the $L^- \to \nu_L + \pi^-$ decay is given in the center-of-mass frame of e^+e^- as

$$\left(\frac{d\sigma}{dx\, d\cos\theta}\right)(e^-;\pi^-) = \frac{\pi\alpha^2}{2s} r \left[1 + \cos^2\theta - \frac{4 g_a P}{1 + g_a{}^2}(2x-1)\cos\theta\right], \tag{2.4}$$

where s is the c.m. energy squared; x, defined by $2E_\pi/\sqrt{s}$, takes values in the region of

$$\tfrac{1}{2}[1 - (1 - 4m_L{}^2/s)^{1/2}] \le x \le \tfrac{1}{2}[1 + (1 - 4m_L{}^2/s)^{1/2}];$$

r is the branching ratio $\Gamma(L^- \to \nu_L + \pi^-)/\Gamma(L^- \to \text{all})$; and P is the magnitude of the beam polarization. In Eq. (2.4) we have ignored $m_N{}^2/s$ and $m_L{}^2/s$ (≤ 0.01 for $m_L = 1.8$ GeV above $\sqrt{s} = 20$ GeV). The bracket $(e^-;\pi^-)$ in the left-hand side indicates that e^- is polarized longitudinally and π^- is measured inclusively. By the same calculation, we find

$$\left(\frac{d\sigma}{dx\, d\cos\theta}\right)(e^+;\pi^-) = \frac{\pi\alpha^2}{2s} r \left[1 + \cos^2\theta + \frac{4 g_a P}{1 + g_a{}^2}(2x-1)\cos\theta\right] \tag{2.5}$$

when e^+ is longitudinally polarized. Here the longitudinal polarization of e^+ is along the direction of its own momentum (opposite to that of e^-). For the processes in which positively charged pions from the two-body L^+ decay are measured inclusively, we obtain through CP invariance

$$\left(\frac{d\sigma}{dx\,d\cos\theta}\right)(e^-;\pi^+)=\left(\frac{d\sigma}{dx\,d\cos\theta}\right)(e^+;\pi^-), \qquad (2.6)$$

$$\left(\frac{d\sigma}{dx\,d\cos\theta}\right)(e^+;\pi^+)=\left(\frac{d\sigma}{dx\,d\cos\theta}\right)(e^-;\pi^-), \qquad (2.7)$$

where the angle θ for π^+ is measured from the direction of the e^- beam momentum just as for the π^- emission angle. It is our purpose to investigate the terms linear in $\cos\theta$ in Eqs. (2.4) and (2.5).

III. NUMERICAL ESTIMATE

From $\sqrt{s}=3.8$ to 7.4 GeV, $d\sigma/dx$ scales reasonably well above $x=0.5$.[5] By assuming the scaling, therefore, we can estimate the hadrons near the high-x end at $\sqrt{s}\gtrsim 20$ GeV that do not come from the heavy leptons. The asymmetry to be measured is[6]

$$\begin{aligned} A(e^-;\pi^-) &\equiv \tfrac{1}{2}\left[s\frac{d\sigma}{dx\,d\cos\theta}(e^-;\pi^-)_{0^\circ}\right.\\ &\qquad\left.- s\frac{d\sigma}{dx\,d\cos\theta}(e^-;\pi^-)_{180^\circ}\right]\\ &= -\pi\alpha^2 rP\frac{2g_a}{1+g_a^{\,2}}(2x-1). \end{aligned} \qquad (3.1)$$

This asymmetry may be detected in three other measurements: $A(e^-;\pi^+)$, $A(e^+;\pi^-)$, and $A(e^+;\pi^+)$. One can enhance the effect by taking the combination

$$A\equiv[A(e^-;\pi^-)+A(e^+;\pi^+)]-[A(e^-;\pi^+)+A(e^+;\pi^-)]. \qquad (3.2)$$

This quantity A should be compared with $s(d\sigma/dx\,d\cos\theta)$ at $\theta=0^\circ$ and 180° of the pions that are emitted symmetrically in forward and backward directions. Let us call those pions background pions. By extrapolating the data from lower energies by scaling, we find that in $0.9<x<1.0$

$$s\left(\frac{d\sigma}{dx\,d\cos\theta}\right)_{\text{background},\,0^\circ}\simeq 50\ \text{nb GeV}^2 \qquad (3.3)$$

for the sum of π^- and π^+ (and possibly $K^\pm$), provided that the $\cos\theta$ distribution is $\propto 1+\cos^2\theta$ for the background pions.[5] On the other hand, with the decay branching ratio $r=0.10$,[7] $g_a=\pm 1$, namely $V\pm A$, and $P=0.90$, the asymmetry in cross sections turns out to be

$$\begin{aligned} A &= [A(e^-;\pi^-)+A(e^+;\pi^+)]-[A(e^-;\pi^+)+A(e^+;\pi^-)]\\ &= \mp 2.6(2x-1)rP\times 10^2\ \text{nb GeV}^2. \end{aligned} \qquad (3.4)$$

In the region of $0.9<x<1.0$, this is as large as

$$A=\mp 21\ \text{nb GeV}^2. \qquad (3.5)$$

The asymmetry of this size is easily distinguished from the asymmetry of other origins, which we will discuss in the following section.

IV. ASYMMETRY OF OTHER ORIGINS

If there are charmed hadrons that are stable against strong and electromagnetic interactions, they may emit pions through weak decay to produce the asymmetry. However, if such stable charmed hadrons are pseudoscalar mesons, a simple kinematics shows that there will be no $\cos\theta$ asymmetry in one-particle inclusive spectra. When there are such hadrons of nonzero spin, they can, in principle, cause an asymmetry. But, strong damping of hadronic form factors suppresses severely two-particle channels, and when charmed hadrons are produced together with other hadrons, the chance that a secondary decay pion reaches the high-x end of the spectrum is negligibly small because the x distribution falls off very fast towards $x=1$ in the case of multibody states. Therefore, we can safely ignore the effect due to decays of metastable hadrons.

The other source of the asymmetry is the neutral-W-boson process that competes with the one-photon annihilation. It depends on specific models of weak interactions. If we choose, for instance, the four-quark model of Salam and Weinberg, we find the asymmetry

$$\begin{aligned} \frac{A(e^-;\pi^-)}{s(d\sigma/dx\,d\cos\theta)_{\text{background},\,0^\circ}} &\simeq 7.7\times 10^{-5}\left(\frac{s/m_N^{\,2}}{1-(s/M_W^{\,2})\cos^2\theta_W}\right)\\ &\quad\times[1+(4\sin^2\theta_W-1)P]\rho_-, \end{aligned} \qquad (4.1)$$

$$\rho_-=\nu\overline{W}_3^{(ew)}(\pi^-)/m_\pi\overline{W}_1^{(e)}(\pi^-), \qquad (4.2)$$

where θ_W is Weinberg's angle, M_W is the charged-W-boson mass, $\overline{W}_1^{(e)}(\pi^-)$ is the inclusive structure function $\overline{W}_1$ for π^- with the electromagnetic currents, and $\overline{W}_3^{(ew)}(\pi^-)$ is the inclusive structure function $\overline{W}_3$ for π^- with one electromagnetic current and one weak current. Similarly,

$$\begin{aligned} \frac{A(e^-;\pi^+)}{s(d\sigma/dx\,d\cos\theta)_{\text{background},\,0^\circ}} &\simeq 7.7\times 10^{-5}\left(\frac{s/m_N^{\,2}}{1-(s/M_W^{\,2})\cos^2\theta_W}\right)\\ &\quad\times\{1+(4\sin^2\theta_W-1)P\}\rho_+, \end{aligned} \qquad (4.3)$$

with ρ_+ being a ratio of structure functions for π^+ in parallel to Eq. (4.2). Charge-conjugation invariance of strong interactions requires that $\rho_- = -\rho_+$. Further, CP invariance of overall processes leads us to

$$A(e^+;\pi^+) = -A(e^-;\pi^-)_{P\to -P}, \quad (4.4)$$

$$A(e^+;\pi^-) = -A(e^-;\pi^+)_{P\to -P}, \quad (4.5)$$

for processes in which the e^+e^- pair annihilates through one photon or one neutral W boson. On the right-hand sides of Eqs. (4.4) and (4.5), the subscripts indicate that the polarization P is to be reversed in sign. If one estimates ρ_- and ρ_+ in the simple parton model, an upper bound is set on $|\rho_- - \rho_+|$;

$$|\rho_- - \rho_+| = \frac{6}{5}\frac{|u(\pi^+) - u(\pi^-)|}{u(\pi^+) + d(\pi^+) + s(\pi^+) + c(\pi^+)},$$
$$\leq \frac{6}{5}. \quad (4.6)$$

Because of Eqs. (4.4) and (4.5), the P-independent terms cancel each other in the sums $A(e^-;\pi^-) + A(e^+;\pi^+)$ and $A(e^-;\pi^+) + A(e^+;\pi^-)$. A net contribution to

$$A = [A(e^-;\pi^-) + A(e^+;\pi^+)] - [A(e^-;\pi^+) + A(e^+;\pi^-)]$$

is proportional to $4\sin^2\theta_W - 1$, which is a small number. One thus obtains with $\sin^2\theta = 0.3$ the upper bound on the asymmetry due to the neutral W boson as

$$\left|\frac{A}{s(d\sigma/dx\,d\cos\theta)_{\text{background},\,0^\circ}}\right| < 3.5\times 10^{-2} \quad (4.7)$$

at $\sqrt{s} = 20$ GeV for $M_W = 50$ GeV and $P = 0.90$. This is much smaller than $\sim 40\%$, the value that is expected for the asymmetry due to pions from the heavy leptons. To make sure that the neutral-W-boson annihilation is really small, one should measure the asymmetry at different energies to see its energy dependence. The asymmetry due to the heavy leptons scales precisely, while the asymmetry due to the neutral W boson increases linearly in s or even faster if the neutral-W-boson mass is not too heavy.

Finally, one might suspect that the interference between one-photon and two-photon processes can cause the asymmetry in $\cos\theta$. But even at highest PEP and PETRA energies this is expected to be no more than several percent.[8] Moreover, charge-conjugation invariance of overall processes requires that $A(e^-;\pi^-) = -A(e^+;\pi^+)$ and $A(e^-;\pi^+) = -A(e^+;\pi^-)$, and therefore no effect remains in the combination

$$A = [A(e^-;\pi^-) + A(e^+;\pi^+)] - [A(e^-;\pi^+) + A(e^+;\pi^-)].$$

V. SUMMARY

With longitudinally polarized e^+e^- beams, one can test clearly whether the weak current of the heavy leptons is $V-A$ or $V+A$. The asymmetry in $\cos\theta$ of the inclusive pion production is quite large near the high-energy end of the x distribution, and its sign depends on whether the current is $V-A$ or $V+A$. Other sources of the asymmetry that may compete turn out to be either sufficiently small or, if not, unambiguously separable by the center-of-mass energy dependence. We have assumed in this paper that the heavy-lepton mass is about 1.8 GeV and that the decay obeys the universality of weak interactions. The branching ratio $\Gamma(L\to\nu_L\pi)/\Gamma(L\to\text{all})$ is uniquely determined for such leptons. If there are heavier leptons, say, of mass ~ 6 GeV, they would not contribute significantly to the asymmetry near $x=1$, since their branching ratio into the two-body ($\nu\pi$) channel is negligibly small ($\sim 1.3\%$).[7] However, the universality should not be taken for granted at all; even the assumption that the heavy leptons cause the μe events at SPEAR has not been established. The particles leading to the μe events may be entirely new species that we have not known. It is therefore highly desirable to study carefully their decay modes in the region where the standard picture of the heavy leptons gives unambiguous and indisputable predictions.

Note added. After we had submitted this paper, we received a paper by Chao and Schwitters[9] in which they point out that a complete treatment of depolarization effects including quantum fluctuations leads generally to very small polarizations. One has to choose carefully beam energies and duration of beam storage in order to achieve large polarizations. Although large beam polarizations seem to be much harder to realize than we have anticipated, experimentalists will attempt this difficult task if there are sufficient justifications to do so.

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[5]See for a summary R. F. Schwitters, in *Proceedings of the 1975 International Symposium on Lepton and Photon Interactions at High Energies, Stanford, California*, edited by W. T. Kirk (SLAC, Stanford, 1976), p. 5; and new preliminary data from SLAC-LBL Magnetic Detector Group [W. Chinowsky (private communication)].

[6]It is easier to measure an asymmetry between the forward and backward hemispheres. With the integral over $\cos\theta$, this asymmetry is given by the right-hand side of Eq. (3.1) multiplied by $\frac{1}{2}$.

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