national accelerator laboratory

NAL-EXP-THY-68

POSSIBLE METHOD OF SEARCHING FOR A WEAK NEUTRAL CURRENT IN $e^+ + e^- \rightarrow \mu^+ + \mu^-$

VU KHAC CUNG
Dept. of Physics, University of Pennsylvania*, Philadelphia, Penn. 19104

A. K. MANN
Dept. of Physics, University of Pennsylvania*, Philadelphia, Penn. 19104
and
National Accelerator Laboratory, Batavia, Illinois 60510

and

E. A. PASCHOS
National Accelerator Laboratory, Batavia, Illinois 60510

ABSTRACT

The possibility of observing interference between a weak interaction amplitude and an electromagnetic amplitude in the reaction $e^+e^- \rightarrow \mu^+\mu^-$ is enhanced by the expectation that the circulating e^+ and e^- beams in a storage ring are polarized. We discuss the salient features of a possible experiment, utilizing that polarization, which allows a search for a primitive weak neutral current to be made at high center of mass energy in that purely leptonic system.

*Work supported in part by the U. S. Atomic Energy Commission.

The experimental study of weak interactions between leptons at large center of mass energy would shed considerable light on the fundamental nature of the weak interaction. No purely leptonic weak interaction has yet been observed apart from muon decay, which occurs essentially as $s = 0$ ($s = 4E_{cm}^2$). Furthermore, the purely leptonic processes that can be studied even with high energy neutrino beams incident on stationary targets are reactions at small s. They will not provide much information on the high energy behavior of lepton-lepton scattering via the weak interaction, although they will probably permit the low energy diagonal current[1] coupling constant to be determined[2] and may perhaps allow a search to be made at small s for neutral leptonic currents.

On the other hand, colliding lepton beams, such as e^+e^- beams in storage rings now under construction, will increase s to values at which departures from the present lowest order weak interaction theory are perhaps more likely to occur. Weak interactions are in general overwhelmed by electromagnetic interactions when lepton beams collide but it may be possible to observe interference between the electromagnetic and weak amplitudes in certain processes. In particular, a weak neutral current would contribute to the reaction $e^+e^- \rightarrow \mu^+\mu^-$ and might be observable, depending on its strength relative to the strength of the electromagnetic current which dominates that reaction.[3,4] This possibility is enhanced by the expectation that under certain conditions the circulating beams in an e^+e^- storage ring may have a very large transverse polarization along or opposite to the direction of the magnetic field due to the emission of synchrotron radiation.[5] Transverse polarization of the e^+e^- beams in a storage ring is expected to modify the angular distribution of the products of e^+e^- collisions more or less profoundly depending on the specific reaction.[5,6,7] In certain angular regions the electromagnetic amplitude is predicted to be significantly less than its value when the e^+e^- beams are unpolarized, which is just what is necessary to increase the relative importance of any weak-electromagnetic interference term.

Recently, at least partial experimental confirmation of beam polarization has been obtained in a simple but ingenious experiment in a low energy storage ring.[8] If this situation continues to hold in higher energy e^+e^- storage rings a search for weak interaction effects in the reaction $e^+e^- \to \mu^+\mu^-$ at high values of s may become realistic.[9] It is our purpose in the remainder of this note to describe the salient features of such an experiment.

Assume that there exist weak neutral currents mediated by an intermediate vector boson W^o through V-A coupling with semi-weak coupling constant g_o. Then to second order in the electromagnetic and semi-weak interactions the two Feynman diagrams shown in Fig. 1 are applicable.

Let

$$\epsilon(s) = \frac{\sqrt{2}\, G_o M_w^2}{4\pi\alpha}\left(\frac{s}{s - M_w^2}\right) \qquad (1)$$

where $s = q^2 = (p_1 + p_2)^2 = (p_3 + p_4)^2$ is the square of the center of mass energy, M_w is the mass of the W^o and, as usual, $g_o^2 = G_o M_W^2/\sqrt{2}$.

We choose the electron and positron momenta as $\vec{p}_- = -\vec{p}_+ = E\hat{n}$. $|\hat{n}| = 1$. Their transverse polarization vectors are $\vec{P}_+ = P_+ \hat{\ell}$ and $\vec{P}_- = P_- \hat{\ell}$ where $|\hat{\ell}| = 1$ and $\hat{\ell}\cdot\hat{n} = 0$. In a storage ring $P_+ = -P_-$ and there is a theoretical upper bound[5] on the polarization magnitudes, $|P_+| = |P_-| = 8\sqrt{3}/15 = 0.924$. Finally, denote the unit vector along the μ^- direction by $\hat{m}$ and let the scattering angles θ and ϕ be defined by

$$\cos\theta = \hat{n}\cdot\hat{m} \; ; \quad \hat{\ell}\cdot\hat{m} = \sin\theta\cos\phi \; ; \quad (\hat{m}\times\hat{n})\cdot\hat{\ell} = \sin\theta\sin\phi \qquad (2)$$

Then

$$\frac{d\sigma_P}{d\Omega} = \frac{\alpha^2}{8s}\Big\{\Big[2 - \sin^2\theta\left(1 + |P_+||P_-|\cos 2\phi\right)\Big] + \epsilon(s)\left(1-P\right)\Big[2 - \sin^2\theta\left(1+|P_+||P_-|\cos 2\phi\right) + 2\cos\theta\Big] + \epsilon^2(s)\left(1-P\right)\left(1+\cos\theta\right)^2\Big\} \qquad (3)$$

where $P = \pm 1$ is the muon helicity.

In the limit $\epsilon(s)\to 0$ the electromagnetic cross section is recovered and for $|P_+|\;|P_-| = 0$, Eq. (3) agrees with the corresponding equation in Ref. 3.

The longitudinal polarization of the outgoing muons, P_L, is given by

$$P_L(\theta,\phi) = \frac{d\sigma_+ - d\sigma_-}{d\sigma_+ + d\sigma_-} = -\epsilon(s)\left[1 + f(\theta,\phi)\right] \qquad (4)$$

and the asymmetry, A, for the spin averaged cross section by

$$A(\theta,\phi) = \frac{d\sigma(\theta,\phi) - d\sigma(\pi-\theta,\phi)}{d\sigma(\theta,\phi) + d\sigma(\pi-\theta,\phi)} = \epsilon(s) f(\theta,\phi) \qquad (5)$$

where

$$f(\theta,\phi) = \frac{2\cos\theta}{2 - \sin^2\theta\left(1 + |P_+||P_-|\cos 2\phi\right)} \qquad (6)$$

We have neglected terms of order $\epsilon^2(s)$ and also lepton masses. It is clear that $f(\theta,\phi)$ is a maximum at $\phi = 0$ and π and can become large for large $|P_+|\,|P_-|$.[10] In Fig. 2 we plotted $f(\theta,\phi)$ for $|P_+| = |P_-| = 0.924$ to show that $f(\theta,\phi)$ rises rapidly from zero at $\theta = \pi/2$ to a broad maximum at $\theta \simeq 75^\circ$ and then falls off slowly with θ.

It is important to note that the two-photon exchange contributions to the muon polarization in $e^+e^- \rightarrow \mu^+\mu^-$ has previously been calculated[7] and yields

$$P_L(2\gamma) = -\alpha \frac{\sin^2\theta \; X(\theta) \; \sin 2\phi}{\left[2 - \sin^2\theta \left(1 + |P_+||P_-| \cos 2\phi\right)\right]} \tag{7}$$

where

$$X(\theta) = -2|P_+||P_-| \left\{ \frac{1}{\sin^2\theta} + 2^{-1}\cos\theta \left[(\sin\frac{\theta}{2})^{-4} \ln\cos\frac{\theta}{2} - (\cos\frac{\theta}{2})^{-4} \ln\sin\frac{\theta}{2} \right] \right\}. \tag{8}$$

Observe that $P_L(2\gamma)$ vanishes at $\phi = 0$ and π where the weak interaction contribution is a maximum. Furthermore, in an experiment with ϕ averaged over the angular intervals, say, 340° to 20° and 160° to 200° (see below), $P_L(2\gamma)$ averages to zero over each of those intervals. It is of particular interest to determine the magnitude of $A(2\gamma)$ since an experiment to measure the asymmetry (Eq. 5) is considerably simpler than one to measure the longitudinal polarization (Eq. 4). The absorptive contribution to $A(2\gamma)$ is zero[7] in an experiment that averages over muon spin directions. The contribution of the real part of the amplitudes to $A(2\gamma)$ is expected to be different from zero, but has not yet been explicitly evaluated.[11] The usual external bremsstralung will not lessen the asymmetry A if the final states are chosen to include muons that are collinear within reasonable accuracy.

For $G_o = G$, the weak coupling constant associated with the singly-charged weak current, and in the absence of a neutral boson, one obtains, for example,

$$A\left(s = 64\ \text{GeV}^2,\ \phi = 0,\ \theta = 65^\circ\right) = -2.0\%$$
$$P_L\left(s = 64\ \text{GeV}^2,\ \phi = 0,\ \theta = 65^\circ\right) = 3.1\% \tag{9}$$

The form of $f(\theta, \phi)$ in Fig. 2 indicates that an experiment to measure A with ϕ averaged over the intervals 340° to 20° and 160° to 200° and θ over the intervals 50° to 80°, 100° to 130°, 230° to 260° and 280° to 310° would yield a counting rate of roughly $2L \times 10^{-31}$ counts per hour at $s = 64\ \text{GeV}^2$, where L is the storage ring luminosity in $\text{cm}^{-2}\ \text{sec}^{-1}$. Thus with $L \geq 10^{32}\ \text{cm}^{-2}\ \text{sec}^{-1}$ it is feasible to carry out an experiment to detect A and in turn a value of G_o approximately equal to G. It might also be possible to detect the presence of a W^o with mass as high as about 8 GeV if the luminosity is large enough to permit runs to be made at several values of s. It is necessary to distinguish the sign of the muon charge in an asymmetry experiment since the μ^- asymmetry at (θ, ϕ) and $(\pi - \theta, \phi)$ is exactly compensated for by the μ^+ asymmetry at the same angles. This can be accomplished by introducing magnetized iron in two of the four arms of the detector at (θ, ϕ) and $(\pi - \theta, \phi)$; an appreciable thickness of iron is desirable anyway in order to select the $\mu^+\mu^-$ final state of the e^+e^- collision.

In conclusion, we emphasize that the search for a primitive weak neutral current by the method described here combines several important features. It is carried out at relatively high and unexplored values of s in purely leptonic system and it is linearly dependent on G_o.

The idea of utilizing the polarization of the circulating beams in an e^+e^- storage ring to make possible a search at high s for a weak neutral current in a purely leptonic system originated in discussions with D. Cline. We have profited from discussions with J. D. Bjorken, B. W. Lee, H. Primakoff and A. Sanda. After we completed this paper we learned of work on the same theme treated from a somewhat different point of view by J. Godine and A. Hankey [12] and also by A. Love. [13]

REFERENCES AND FOOTNOTES

[1]M. Gell-Mann, M. L. Goldberger, N. M. Kroll and F. E. Low, Phys. Rev. 179, 1518 (1969); W. Czyz, C. S. Sheppy and J. D. Walecka, Nuovo Cimento 34, 404 (1964); J. Loevseth and M. Radomski, Phys. Rev. D3, 2686 (1971); K. Fujikawa, Ph. D. Thesis, Princeton University (unpublished) 1970, Phys. Rev. to be published.

[2]Harvard-Pennsylvania-Wisconsin Collaboration, Experimental Proposal 1A, National Accelerator Laboratory (unpublished) 1970.

[3]N. Cabibbo and R. Gatto, Phys. Rev. 124, 1577 (1961); R. Gatto, Proc. Int'l. Symposium on Electron and Photon Interactions at High Energies, Hamburg, 1965, Springer Tracts in Modern Physics 39, 106 (1965). T. Kinoshita, J. Pestieau, P. Roy and H. Terazawa, Phys. Rev. D2, 910 (1970).

[4]S. L. Glashow, J. Iliopoulos and L. Maiani, Phys. Rev. D2, 1285 (1970).

[5]I. M. Ternov, Yu. M. Loskutov and L. I. Korovina, Sov. Phys. JETP 14, 921 (1962); A. A. Kokolov and I. M. Ternov, Sov. Phys. Dokl. 8, 1203 (1964); A. A. Sokolov and I. M. Ternov, Synchrotron Radiation, Pergamon Press, N. Y., 1968.

[6]V. N. Baier, XLVI Corso Scuola Internazionali di Fisica "Enrico Fermi", 4, (1969). Academic Press.

[7]B. Ya Zel'dovich and M. V. Terent'ev, Sov. Jour. of Nucl. Physics 7, 650 (1968).

[8] J. Le Duff, P.C. Marin, P. Petroff and E. Sommer, Proc. of the Int'l. Symposium on Electron and Photon Interactions at High Energies, Cornell University, Ithaca, N.Y., 1971.

[9] A proposal to carry out this search was submitted to SLAC (SP-7) by A.K. Mann, D.B. Cline and D.D. Reeder, (unpublished), 1972. At an energy E = 4 GeV, which is less than the maximum energy planned for an improved storage ring at SLAC, the beam polarization at any time t is given by $P(t) = P_o (1 - e^{-t/\tau})$ where $P_o = 0.924$ is the theoretical limit of the transverse polarization and $\tau = 10$ minutes.

[10] Note that $f(\theta, \phi)$ increases relatively slowly with $|P_\pm|$ up to a value of $|P_\pm| \simeq 0.99$ but increases more rapidly above that value. Any technique that successfully increased the probability per unit time of a radiative transition with spin flip by the particles in the circulating beams would lead to values of $|P_\pm| > 0.924$.

[11] An attempt to estimate higher order terms contributing to $e^+e^- \to \mu^+\mu^-$ in the absence of initial state polarization was made by Furlan, Gatto and Longhi, Physics Letters 12, 262 (1964). A calculation of the real part of the 2-photon diagrams for the polarization condition specified in the present paper is currently in progress.

[12] J. Godine and A. Hankey, MIT Center for Theoretical Physics, Publication No. 279 (to be published).

[13] A. Love, Rutherford Laboratory preprint, RRP/T/11.

FIGURE CAPTIONS

Figure 1: Lowest order Feynman diagrams for $e^+e^- \rightarrow \mu^+\mu^-$.

Figure 2: Plot of $f(\theta, \phi)$ against θ for $\phi = 0$, π and $|P_+| = |P_-| = 0.924$.

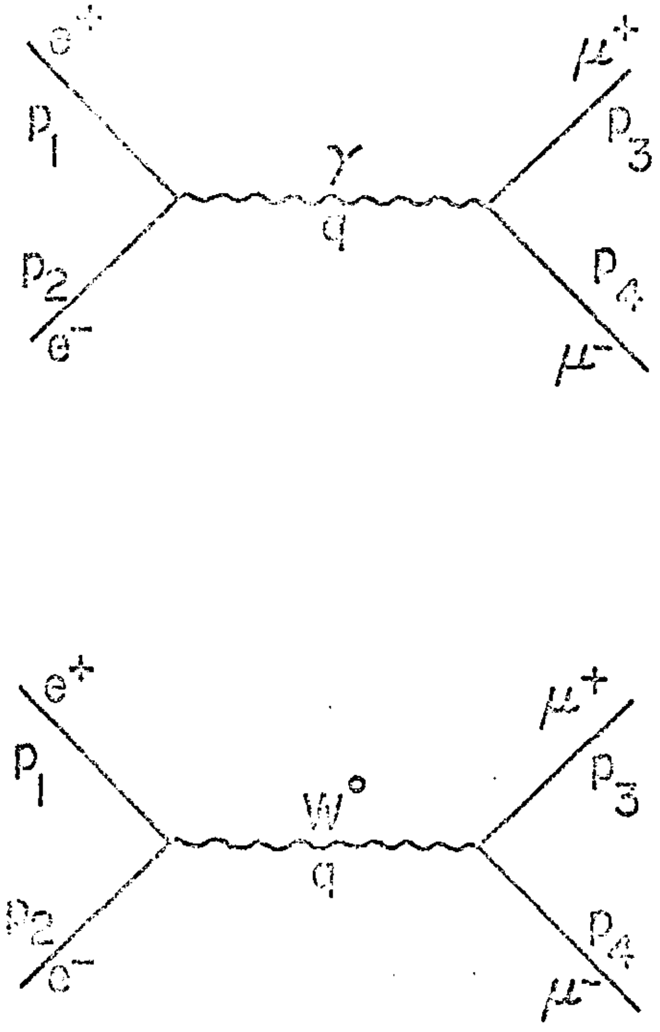

Figure 1

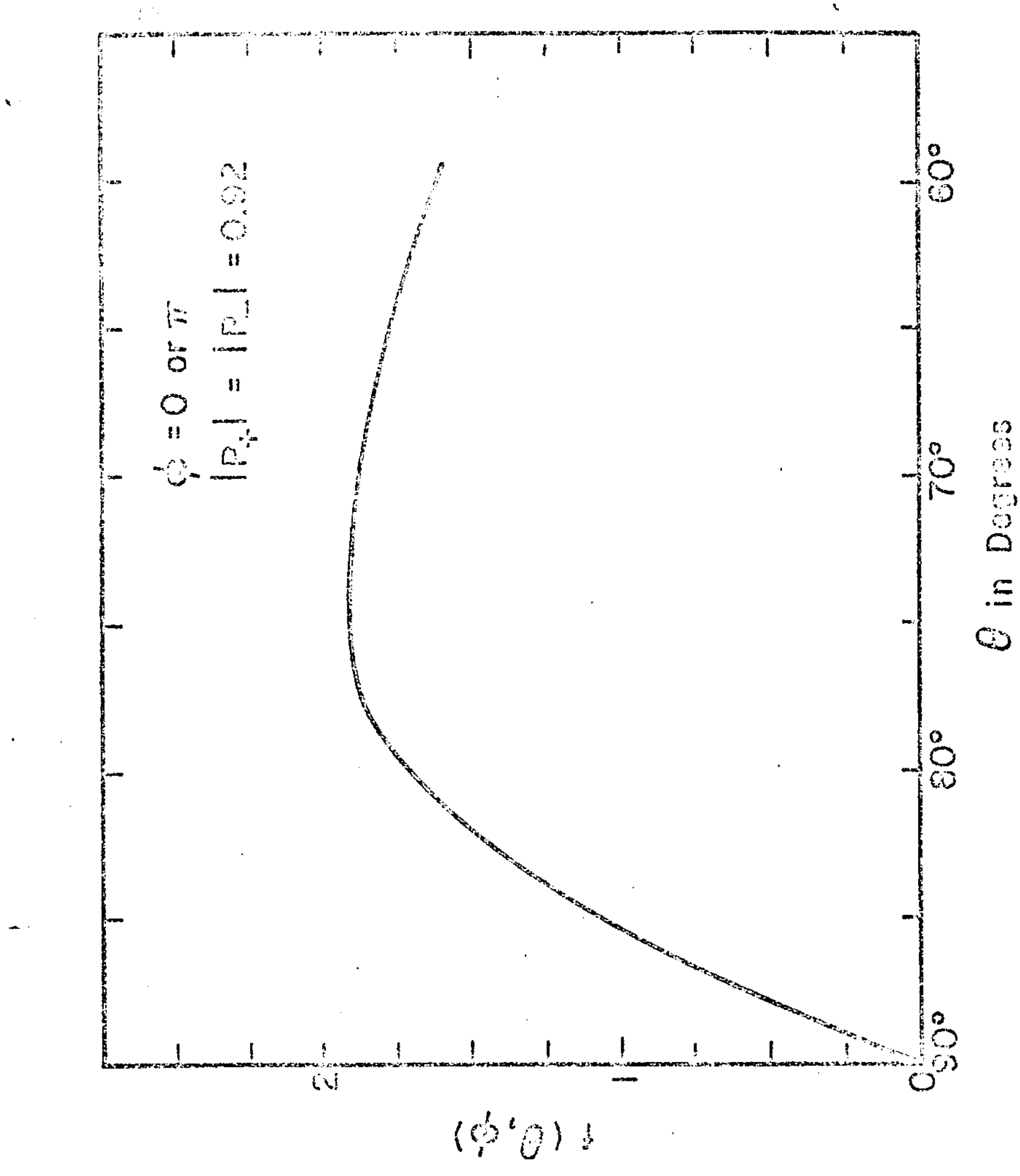

Figure 2

CORRECTIONS

Possible Method of Searching for a Weak Neutral Current in $e^+ + e^- \rightarrow \mu^+ + \mu^-$

NAL-EXP-THY-68

by

Vu Khac Cung, A. K. Mann and E. A. Paschos

1. The equation on page 4, line 4 should read: $\vec{p}_- = -\vec{p}_+ = E\hat{n}$.

2. On page 9, reference 3, the following reference should be added:

   T. Kinoshita, J. Pestieau, P. Roy and H. Terazawa, Phys. Rev. D2, 910 (1970).