1974 [Bull. Amer. Phys. Soc. 19, 571 (1974)].
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[1]P. D. Johnston, M. Kaplan, and N. J. Stone, Phys. Rev. Lett. 32, 784 (1974).
[2]G. H. Fuller and V. W. Cohen, Nucl. Data, Sect. A 5, 433 (1969).
[3]R. Chuckrow and H. H. Stroke, J. Opt. Soc. Amer. 61, 218 (1971).
[4]These assumptions are used in the analysis of both the nuclear-orientation and the spectroscopic data. We note that the value of the nuclear spin of ^{207}Bi does not result from a direct measurement [M. R. Schmorak and R. L. Auble, Nucl. Data, Sect. B 5, 207 (1971)].
[5]A. Bohr and V. F. Weisskopf, Phys. Rev. 77, 94 (1950).
[6]H. H. Stroke, R. J. Blin-Stoyle, and V. Jaccarino, Phys. Rev. 123, 1326 (1961).
[7]I. Lindgren and C. M. Johansson, Ark. Fys. 15, 445 (1959). Their atomic-beam magnetic-resonance experiment, that relied on a "low-field" measurement, together with the insufficiency of the available sample, did not allow the attainment of the usual precision afforded by this technique for hfs determination. The value of the nuclear spin of ^{205}Bi was, however, obtained uniquely.
[8]G. E. Brown, J. Phys. Soc. Jpn., Suppl. 35, S3 (1973).
[9]H. Miyazawa, Progr. Theor. Phys. 6, 263, 801 (1951), and J. Phys. Soc. Jpn., Suppl. 35, 10 (1973).
[10]The required ^{209}Bi hfs interaction constants used were $A(^4P_{1/2}) = 164.18(16)\times 10^{-3}$ cm^{-1} (R. Winkler, private communication.) Published values for this constant are 163.8(5) [L. O. Dickie and F. M. Kelly, Can. J. Phys. 45, 2249 (1967)] and 163.9(6) [R. Chuckrow, P. C. Magnante, and H. H. Stroke, J. Opt. Soc. Amer. 58, 922 (1968)], and $A(^4S_{3/2}) = -14.909(1)\times 10^{-3}$ cm^{-1} [R. S. Title and K. F. Smith, Phil. Mag. 5, 1281 (1960)].
[11]R. Winkler and G. Müller, private communication; G. Müller, D. Eng. thesis, Technische Universität, Berlin, 1974 (unpublished).
[12]M. Kaplan, P. D. Johnston, P. Kittel, and N. J. Stone, Nucl. Phys. A212, 478 (1973).
[13]P. C. Magnante and H. H. Stroke, J. Opt. Soc. Amer. 59, 836 (1969).
[14]J. A. Cameron, I. A. Campbell, J. P. Compton, M. F. Grant, R. W. Hill, and R. A. G. Lines, *Low Temperature Physics—LT9*, edited by J. G. Daunt, D. O. Edwards, F. J. Milford, and M. Yaqub (Plenum, New York, 1965), Pt. B, p. 1033.
[15]P. G. E. Reid, M. Sott, and N. J. Stone, Nucl. Phys. A129, 273 (1969).
[16]R. J. Blin-Stoyle, Proc. Phys. Soc., London, Sect. A 66, 1158 (1953); R. J. Blin-Stoyle and M. A. Perks, *ibid.* 67, 885 (1954).
[17a]A. Arima and H. Horie, Progr. Theor. Phys. 11, 509 (1954), and 12, 623 (1954).
[17b]H. Noya, A. Arima, and H. Horie, Progr. Theor. Phys., Suppl. No. 8, 33 (1958).
[18]See, for example, H. A. Mavromatis, L. Zamick, and G. E. Brown, Nucl. Phys. 80, 545 (1966); H. A. Mavromatis and L. Zamick, *ibid.* A104, 17 (1967); G. F. Bertsch, Phys. Lett. 28B, 302 (1968).
[19]A. Arima, J. Phys. Soc. Jpn., Suppl. 35, S205 (1973); H. Hyuga and A. Arima, *ibid.* 35, S538 (1973).
[20]Miyazawa, Ref. 9.

Comments on Weak Neutral Vector Mesons and Charge Asymmetry in $e^+e^- \to \mu^+\mu^-$†

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We comment on the forward-backward asymmetry in the reaction $e^+e^- \to \mu^+\mu^-$ due to the possible existence of parity-nonconserving weak neutral interactions. Estimates are given for the possibilities that such an interaction is mediated either by a very massive vector boson or by the recently discovered $J(3105)$ or $\psi'(3695)$ particles.

As a result of the discovery of weak neutral currents[1] and the development of gauge theories,[2] the search for parity nonconservation in neutral weak processes has received renewed interest.[3-5] Furthermore, the recent discovery of the $J(3105)$[6,7] and $\psi'(3695)$[8] particles offers the possibility that these particles might be the bosons mediating such interactions. In this note, we suggest a search for parity-nonconserving effects in the reaction $e^+e^- \to \mu^+\mu^-$ in the J and ψ' regions and, if these particles do not mediate parity-nonconserving interactions, in the continuum region. The latter case can provide us with a rather stringent bound on the strength of the interaction in addition to those obtained in Ref. 5.

In the presence of parity-nonconserving, but time-reversal-invariant, interactions, charge-conjugation invariance is also violated. The interaction Hamiltonian for the leptons can be written as

$$\mathcal{H} = e\sum_l \bar{\psi}_l \gamma_\mu \psi_l A^\mu + \sum_i \sum_l g_{il} \bar{\psi}_l \gamma_\mu (a_{il} + i b_{il}\gamma_5)\psi^l W_i^{\ \mu} + \sum_i (g_{i\nu}/\sqrt{2})\bar{\psi}_\nu \gamma_\mu (1 + i\gamma_5)\psi_\nu W_i^{\ \mu}, \tag{1}$$

where the first term is the usual electromagnetic interaction. The summation over l is for $l=\mu, e$ and that over i for any possible weak neutral boson W_i with mass M_i. The parameters a_{il} and b_{il} represent the relative strength of the parity-conserving and -nonconserving interactions and are normalized, i.e., $a_{il}^2+b_{il}^2=1$. From Eq. (1), it is straightforward to show that the cross section for $e^+e^-\to\mu^+\mu^-$ is given by

$$\frac{d\sigma}{d\cos\theta}=\frac{\pi\alpha^2}{2s}\Bigg\{\Bigg[1+\frac{s}{4\pi\alpha}\left(\sum_i\frac{g_{ie}g_{i\mu}a_{ie}a_{i\mu}}{s-m_i^2+im_i\Gamma_i}+\text{c.c.}\right)+\frac{s^2}{(4\pi\alpha)^2}\sum_i\sum_j\frac{g_{ie}g_{i\mu}g_{je}g_{j\mu}(a_{ie}a_{je}+b_{ie}b_{je})(a_{i\mu}a_{j\mu}+b_{i\mu}b_{j\mu})}{(s-m_i^2+im_i\Gamma_i)(s-m_j^2-im_j\Gamma_j)}\Bigg](1+\cos^2\theta)$$
$$+\Bigg[\frac{2s}{4\pi\alpha}\left(\sum_i\frac{4g_{ie}g_{i\mu}b_{ie}b_{i\mu}}{s-m_i^2+im_i\Gamma_i}+\text{c.c.}\right)+\frac{2s^2}{(4\pi\alpha)^2}\sum_i\sum_j\frac{\xi_{ij}g_{ie}g_{i\mu}g_{je}g_{j\mu}}{(s-m_i^2+im_i\Gamma_i)(s-m_j^2-im_j\Gamma_j)}\Bigg]\cos\theta+O(\alpha)\Bigg\},\quad(2)$$

where $\cos\theta$ is the relative angle between e^- and μ^- in the center-of-mass frame, s is the square of the total invariant mass, Γ_i is the width of the boson W_i, and $\xi_{ij}=2(a_{ie}b_{je}a_{i\mu}b_{j\mu}+a\rightleftarrows b)$ $(|\xi_{ii}|\leq 1)$. Because of the $\gamma_5\gamma^\mu$ interaction, the cross section is, although apparently parity invariant, asymmetric under the interchange of μ^+ and μ^- alone. This charge asymmetry results in the forward-backward asymmetry as given by the $\cos\theta$ term in Eq. (2). In terms of partial-wave amplitudes, the asymmetry simply follows from the interference of the ${}^3S_1$ and ${}^3P_1$ amplitudes, which have both opposite parities and opposite charge-conjugation properties. The higher-order electromagnetic interactions, such as the interference between two-photon and one-photon processes, can also give rise to a forward-backward asymmetry.[9] In the following, their effects will be discussed together with the effects due to the weak interaction. We define the forward-backward asymmetry parameter as

$$\eta=(\sigma_F-\sigma_B)/(\sigma_F+\sigma_B),\quad(3)$$

where

$$\sigma_F=\int_0^1\frac{d\sigma}{d\cos\theta}\,d\cos\theta,\quad \sigma_B=\int_{-1}^0\frac{d\sigma}{d\cos\theta}\,d\cos\theta.$$

(i) We first discuss the possibility that the weak interaction is mediated by a very massive boson, as in gauge theories. Then, the weak-interaction contribution is

$$\eta_{\text{weak}}=\frac{3}{4}\left[-\frac{8g_eg_\mu b_eb_\mu}{4\pi\alpha M_w^2}s+\xi\left(\frac{g_eg_\mu}{4\pi\alpha M_w^2}\right)^2s^2\right].\quad(4)$$

For $M_w^2\gg s$ and $g_eg_\mu/M_w^2\sim G_F$, η_{weak} is of the order of $(5\times10^{-4}\ \text{GeV}^{-2})s$, while the contribution from the interference between the two-photon and one-photon processes is of the order of a few percent. But, since this electromagnetic contribution can be exactly calculated, we can still learn about the weak interaction. For example, if a relatively simple measurement of η_{weak} is performed at $s\sim 50\ \text{GeV}^2$ to a 10% level, we can obtain a bound

$$|g_eg_\mu b_eb_\mu/M_w^2|\lesssim\tfrac{1}{3}\times10^{-4}\ \text{GeV}^{-2}\quad\text{if } |\eta_{\text{weak}}|\lesssim 10\%.\quad(5)$$

Using the notations of Ref. 5, we have equivalently

$$|\epsilon_{e\mu}{}^{AA}|\lesssim\tfrac{1}{3}\ \text{if } |\eta_{\text{weak}}|\lesssim10\%,\quad(5a)$$

where the above parameters are related to the parameters in Eq. (1) by

$$\epsilon_{e\mu}{}^{AA}G_F/2\pi\alpha\sqrt{2}=g_eg_\mu b_eb_\mu/M_w^2.\quad(6)$$

Similarly, if we can subtract the Coulomb-scattering contribution in the reaction $e^+e^-\to e^+e^-$, we can obtain a comparable bound for $\epsilon_{ee}{}^{AA}$ and, including hadronic form factors, we can also study the two-body hadronic final states to obtain bounds for $\epsilon_{eh}{}^{AA}$. These types of effects on the weak neutral currents and the bounds are at least as stringent as the ones considered in Ref. 5.

Although it is relatively simple to obtain bounds, it may not be practical to perform precise measurements on the weak contributions to the asymmetry. For example, if $M_w^2\gg s$ and $g_eg_\mu/M_w^2\sim G_F/\sqrt{2}$, $\epsilon_{e\mu}{}^{AA}\sim2\pi\alpha=0.05$, it would require 10^5 events to measure a few percent asymmetry. In this case, it may be more feasible to detect parity-nonconserving effects in atomic physics.[3-5,10] On the other hand, if the vector mesons are relatively light, such as being the J(3105) and/or ψ'(3695), resonances can greatly enhance the effects.

(ii) We now discuss the possibility that the J and/or ψ' particles may mediate a parity-nonconserving weak interaction. Let us first point out the numerical proximity between the coupling strength for neutrino-electron scattering as observed in Gargamelle and that for $e^+e^-\to J$ or ψ'.

From Eq. (1), the total cross section for $\bar{\nu}_\mu e^- \to \bar{\nu}_\mu e^-$ is

$$\sigma(\nu e \to \nu e) \cong \sum_{i,j=J,\psi'} \frac{g_{i\nu} g_{j\nu} g_{ie} g_{je}}{4\pi m_i^2 m_j^2}(a_{ie} a_{je} + b_{ie} b_{je}) 2 m_e E_\nu^{\text{lab}}, \tag{7}$$

while experimentally, we have[1]

$$\sigma(\nu e \to \nu e) \lesssim (0.8 \times 10^{-41}\ \text{cm}^2/\text{GeV}) E_\nu. \tag{8}$$

Comparison between Eqs. (7) and (8) yields

$$(g_\nu^2/4\pi) g_e^2/4\pi \lesssim 8 \times 10^{-12}. \tag{9}$$

To obtain an estimate of the coupling strength in $e^+e^- \to J$ or ψ', we employ unitarity, which results in

$$\int_{m-\Gamma/2}^{m+\Gamma/2} \sigma(e^+e^- \to \text{anything})\, dE \simeq \pi g_e^2/4m, \tag{10}$$

where the background subtractions near these resonances are negligible. For $m = 3105$ MeV, the integral in Eq. (10) is approximately 6000 nb MeV, which yields

$$g_e^2/4\pi \simeq 3 \times 10^{-6}. \tag{11}$$

Notice that the results in Eqs. (9) and (11) are comparable to each other if $|g_\nu| \sim |g_e|$.

If J or ψ' can have a $\gamma_5 \gamma_\mu$ coupling to the leptons and $\xi > \alpha$, then the asymmetry in the resonance regions is dominated by the weak interaction. From Eqs. (2) and (3), we have

$$\eta \simeq \tfrac{3}{4}\xi. \tag{12}$$

We strongly urge the measurements on $d\sigma/d\cos\theta$ or η which will provide important understanding of these new particles.

As a result of the extreme narrowness of these resonances, the asymmetry will rapidly decrease by orders of magnitude even when $\sqrt{s}$ is only a few hundred MeV away from the peaks and, unlike the high-m_w case, it will decrease with increasing s.

To conclude, we strongly urge the measurement of the asymmetry in $e^+e^- \to \mu^+\mu^-$. Although a confirmation of the existence of the asymmetry cannot be regarded as conclusive evidence for the interaction given by Eq. (1), such will be an intriguing possibility. An absence of the asymmetry will also provide very stringent bounds on the parity-nonconserving interactions.

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[1]See, for example, H. Wachsmuth, in Proceedings of the SLAC Summer Institute on Particle Physics, Stanford, California, 1973, SLAC Report No. SLAC-167, 1973 (unpublished), Vol. II, pp. 235–249.

[2]For a recent review, see, for example, M. A. B. Bég and A. Sirlin, Rockefeller University Report No. COO-2232B-47, 1974 (to be published).

[3]M. A. Bouchiat and C. C. Bouchiat, Phys. Lett. 49B, 111 (1974).

[4]G. Feinberg and M. Y. Chen, Phys. Rev. D 10, 190 (1974).

[5]M. A. B. Bég and G. Feinberg, Phys. Rev. Lett. 33, 606 (1974).

[6]J. J. Aubert *et al.*, Phys. Rev. Lett. 33, 1404 (1974).

[7]J.-E. Augustin *et al.*, Phys. Rev. Lett. 33, 1406 (1974); see also C. Bacci *et al.*, *ibid.* 33, 1408 (1974).

[8]G. S. Abrams *et al.*, Phys. Rev. Lett. 33, 1453 (1974).

[9]F. A. Berends, K. J. F. Gaemers, and R. Gastmans, to be published, and references therein.

[10]W. Williams and R. Lewis, private communication.