PHYSICAL REVIEW D VOLUME 23, NUMBER 9 1 MAY 1981

High-energy manifestations of heavy quarks in axial-vector neutral currents

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(Received 7 November 1980)

A recent work by Collins, Wilczek, and Zee has attempted to manifest the incompleteness of the decoupling theorem in the axial-vector neutral currents at low energies. In the spirit of their work, we calculate corrections of the axial-vector neutral currents by virtual-heavy-quark exchange in the high-energy e^+e^- processes and estimate some observable quantities sensitive to virtual-heavy-quark masses which may be compared with experimental data at LEP energies.

An interesting question for particle physicists is how many flavors exist. Can one find evidence for the existence of quarks which are too heavy to be produced at present accelerator energies? The decay width of the Z meson might answer this question, if the standard model is correct and there are no heavy neutral leptons at all. Another way to answer this question may be to seek phenomena which are induced by virtual-heavy-particle exchange.

There is a widespread belief that one can neglect the contribution of virtual heavy particles below their thresholds because of the decoupling theorem of Appelquist and Carazzone[1]: In renormalizable field theories with widely different mass scales, heavy-particle effects are suppressed by the factor E/M at low energies $E \ll M$, M being the mass of the heavy particles. However some authors found several processes[2-4] to which the decoupling theorem is not applicable and, therefore, in which heavy particles do not decouple at low energies in gauge theories. One such example is the triangle process[4] represented by Fig. 1, which gives corrections to the axial-vector coupling of the neutral current through the strong interaction. Collins, Wilczek, and Zee have evaluated the corrections coming from each doublet U, D of charge $\frac{2}{3}$, $-\frac{1}{3}$ heavy quarks at small momentum transfers to be

$$\Delta J_\mu^5 = (\bar{u}\gamma_\mu\gamma_5 u + \bar{d}\gamma_\mu\gamma_5 d)\tfrac{1}{4}[\bar{g}^2(M_U)/4\pi^2] \times [\bar{g}^2(M_D)/4\pi^2]\ln M_U^2/M_D^2\,, \tag{1}$$

where $\bar{g}$ is the running strong-interaction coupling and $M_{U(D)}$ is the U (D) quark mass.

In this paper we estimate the heavy-particle effects on the axial-vector neutral current at nonvanishing momentum transfers ($P^2 \neq 0$), which will be compared with experiments when neutral-current data in high-energy e^+e^- annihilation become more precise. This, as we shall see in the following, will be useful to predict the existence of heavy quarks below their thresholds.

For simplicity we consider the bare axial-vector neutral current $J_{0\mu}^5$ involving one light-quark doublet (u, d) and one heavy-quark doublet (U, D):

$$J_{0\mu}^5 = \tfrac{1}{2}(\bar{u}\gamma_\mu\gamma_5 u - \bar{d}\gamma_\mu\gamma_5 d) + \tfrac{1}{2}(\bar{U}\gamma_\mu\gamma_5 U - \bar{D}\gamma_\mu\gamma_5 D)\,. \tag{2}$$

The extension to a more general case is obvious. The strong interaction through the heavy-quark loop induces an effective axial-vector isosinglet neutral current

$$\Delta J_\mu^5 = C(\bar{u}\gamma_\mu\gamma_5 u + \bar{d}\gamma_\mu\gamma_5 d)\,. \tag{3}$$

The coefficient C is given by use of a function F as

$$C = 3(\alpha_s/\pi)^2[F(M_U^2/P^2) - F(M_D^2/P^2)] \tag{4}$$

at nonvanishing P^2. The function F is obtained from the real part of the two-loop integral in Fig. 1 as

$$F(M^2/P^2) = \int_0^1 dx \int_0^{1-x} dy \int_0^1 dr_1 \int_0^{1-r_1} dr_2 \int_0^{1-r_1-r_2} dr_3 \Big\{ \ln W + \frac{1-x-y}{9W}[-11XY + 5(xY + yX) + 3(xX + yY) - (x+y)^2] + \frac{(1-x-y)^2}{9W^2} XY[-2XY + 2(xY + yX) + (xX + yY) - (x+y)^2] \Big\}\,, \tag{5}$$

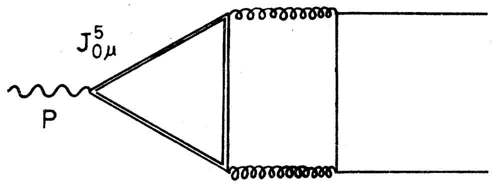

FIG. 1. Contribution of the triangle diagram to the axial-vector neutral current through the strong interactions.

where

$$X = xr_1 + (x+y)r_2,$$

$$Y = yr_1 + (x+y)r_3,$$

and

$$W = r_1(x+y)(M^2/P^2 - xy) - (1-x-y)XY.$$

In the vanishing limit of P^2, our result (3) coincides with that of Collins *et al.* (1).

Numerical examples are shown in Figs. 2 and 3 for $\alpha_s = 0.1$ [between $P^2 = (100)^2$ and $(300)^2$ $(\mathrm{GeV}/c)^2$] which we extrapolate by use of the renormalization-group equation from α_s given by the deep-inelastic scattering experiments. In Fig. 2 we plot the values of C as a function of M_U fixing P^2 at $(90)^2$ $(\mathrm{GeV}/c)^2$ and M_D at 50, 60, and 100 GeV/c^2. The P dependence of C depicted in Fig. 3 corresponds to the following choices of (M_U, M_D) in GeV/c^2: (200, 50), (100, 50), and (200, 100). These results are summarized as follows. The value of C has weak dependence on

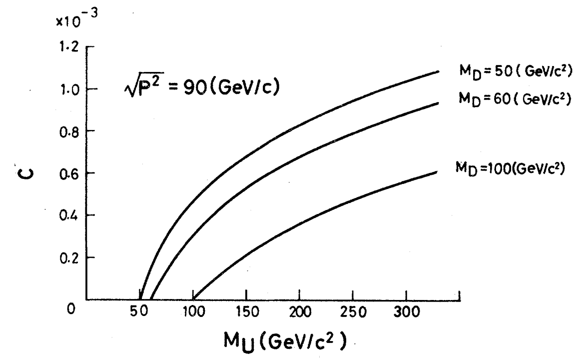

FIG. 2. The coefficient C of the isosinglet axial-vector neutral current as a function of M_U for $M_D = 50$, 60, and 100 GeV/c^2.

P^2. Even just below the thresholds of heavy quarks, we can only expect about a 50% increase of C in comparison with the value of C at $P^2 = 0$. The amount of the correction to the axial-vector neutral current from each heavy-quark doublet is almost dependent only on the mass ratio M_U/M_D except P^2 being around the heavy-quark threshold. The ratio of the induced isosinglet axial-vector current to the isotriplet one is about 0.2% independent of P^2 when $M_U/M_D = 5$. Here we would like to comment on the numerical result of Collins *et al.* They have estimated the contribution from c and s quarks with $M_c/M_s = 5$ and $\bar{g}^2/4\pi^2 = \frac{1}{4}$, i.e., $\alpha_s = 0.79$ to obtain a 10% correction. Note that they used α_s larger than the conven-

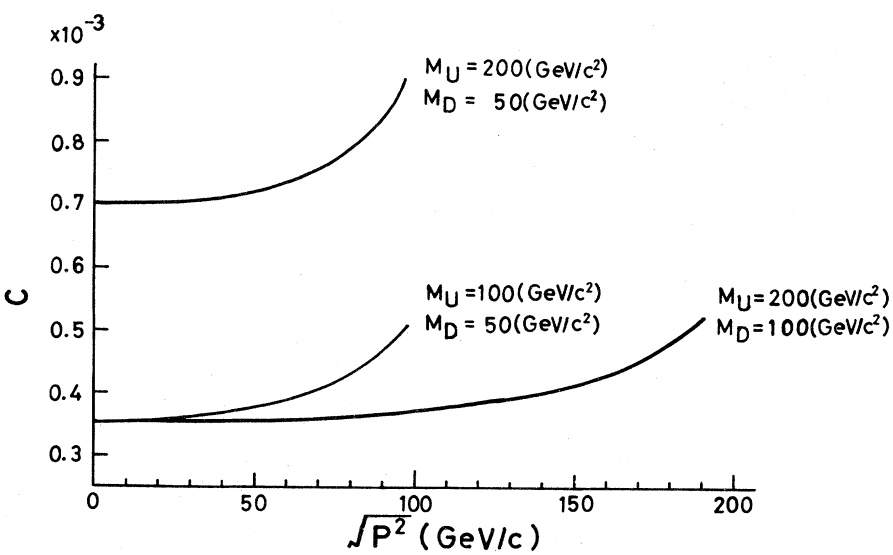

FIG. 3. The coefficient C of the isosinglet axial-vector neutral current as a function of $(P^2)^{1/2}$ for the choices of (M_U, M_D): (200, 50), (100, 50), and (200, 100) in GeV/c^2.

tional value at low energies by a factor 3 and our α_s at $P^2 = (90)^2$ (GeV/c)^2 by a factor 8.

We shall show here two examples of the experimental quantities which are affected by the presence of the isosinglet axial-vector current. One is the ratio $\Gamma(Z\to u\bar{u})/\Gamma(Z\to d\bar{d})$ and the other an asymmetry parameter

$$A = \frac{\int_0^1 d\cos\theta\, d\sigma/d\cos\theta - \int_{-1}^0 d\cos\theta\, d\sigma/d\cos\theta}{\int_{-1}^1 d\cos\theta\, d\sigma/d\cos\theta(e^-e^+\to Z\to u\bar{u}+d\bar{d})}\ .$$

These quantities are given by use of the Weinberg angle as

$$\frac{\Gamma(Z\to u\bar{u})}{\Gamma(Z\to d\bar{d})} = \frac{1-\frac{8}{3}\sin^2\theta_W+\frac{32}{9}\sin^4\theta_W+2C+2C^2}{1-\frac{4}{3}\sin^2\theta_W+\frac{8}{9}\sin^4\theta_W-2C+2C^2}$$

and (6)

$$A = \frac{3}{4}\,\frac{1-4\sin^2\theta_W}{1-4\sin^2\theta_W+8\sin^4\theta_W} \times \frac{1-2\sin^2\theta_W-\frac{4}{3}C\sin^2\theta_W}{1-2\sin^2\theta_W+\frac{20}{9}\sin^4\theta_W+2C^2}$$

in the Weinberg-Salam model with the strong-interaction correction. When we discover the neutral weak boson Z^0, we will know the value of $\sin^2\theta_W$ with high accuracy. If we assume $\sin^2\theta_W = \frac{1}{4}$ and that there are heavy quarks with masses of 50 and 200 GeV/c^2, for example, then we get

$$\frac{\Gamma(Z\to u\bar{u})}{\Gamma(Z\to d\bar{d})} = \frac{10}{13}\left(1+\frac{414}{65}C\right) = \frac{10}{13}(1+0.005)\,.$$

It may be possible to detect this 0.5% correction to $\Gamma(Z\to u\bar{u})/\Gamma(Z\to d\bar{d})$ by virtue of the expected high rates from the LEP luminosities in a future high-energy e^+e^- facility.

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