COMMENTS

Quark Anomalous Magnetic Moment and ψ Particles

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Various consequences of the anomalous current introduced to explain the production and decay of the newly discovered ψ particles are discussed. In particular it is shown that Adler's neutrino sum rule would be modified in such a way that it would not be consistent with the scaling behavior of the structure functions.

Recently, Das *et al.*[1] have proposed an interesting phenomenological model to explain the newly discovered ψ particles.[2] In this model the extreme narrowness of $\psi(3.1)$ is explained by the introduction of an extra additive quantum number which has been named "paracharge" (Z) and which is conserved in strong interactions. The production and decay of the $\psi(3.1)$ particle can be explained by coupling it to an anomalous vector current

$$[V_\mu{}^i(x)]_{\rm anom}=(i\beta/2M)\partial[\bar{\xi}(x)\sigma_{\mu\nu}\tfrac{1}{2}\lambda^i\xi(x)]/\partial x_\nu, \quad (i=1,2,\ldots,15), \tag{1}$$

where $\xi\equiv(u,d,s,\chi)$ are the quartet quarks and β and M are free parameters. Here (u,d,s) is the conventional SU(3) quark triplet with $Z=0$ and χ is an additional SU(3) singlet quark with $Z=1$. Decay widths of $\psi(3.1)$ calculated from the above current seem to be in reasonably good agreement with the available experimental data provided $|\beta|/2M$ is taken to be 0.08 GeV^{-1}. It may therefore be worthwhile to study other consequences of such an anomalous current.

It should be noted that some time ago the present author[3] had in fact introduced such a anomalous current to study the consequences of quarks having anomalous magnetic moment. It is then clear that $\beta/2M$ is the quark anomalous magnetic moment. Thus in Das *et al.*'s model the production and decay of ψ particles is dependent on the intrinsic properties of the basic quarks. Some of the consequences of such an anomalous current are as follows:

(1) The total vector current is now given by the sum of the conventional and the anomalous pieces. Notice however that the vector charge $\int V_0{}^i(x)\,d^3x$ and the conserved-vector-current hypothesis remain unchanged since the anomalous current is chargeless and conserved by itself. Thus, Gell-Mann's charge-algebra, conserved-vector-current, partial conservation of axial-vector current approach remains unaltered. The density algebra will however be modified as follows [I am restricting the discussion to SU(3) generalization to SU(4) is straightforward]:

$$\begin{aligned}[]
[V_0{}^\alpha(x), V_0{}^\beta(y)]_{x_0=y_0}
&= 2f_{\alpha\beta\gamma}\Big\{\mathfrak{F}_0{}^\gamma(x)\delta^{(3)}(\vec{x}-\vec{y})-\frac{\beta^2}{4M^2}\partial_l{}^x\partial_l{}^y[\mathfrak{F}_0{}^\gamma(x)\delta^{(3)}(\vec{x}-\vec{y})]+\frac{\beta}{2M}(\partial_l{}^x-\partial_l{}^y)[T_{0l}{}^\gamma(x)\delta^{(3)}(\vec{x}-\vec{y})]\Big\}\\
&\quad + id_{\alpha\beta\gamma}\frac{\beta^2}{4M^2}\epsilon_{lmn}\partial_l{}^x\partial_m{}^y[A_n{}^\gamma(x)\delta^{(3)}(\vec{x}-\vec{y})],
\end{aligned}\tag{2}$$

$$[V_0{}^\alpha(x), A_0{}^\beta(y)]_{x_0=y_0}=2f_{\alpha\beta\gamma}A_0{}^\gamma(x)\delta^{(3)}(\vec{x}-\vec{y})+\frac{\beta}{2M}d_{\alpha\beta\gamma}\epsilon_{lmn}\frac{\partial}{\partial x_n}[T_{lm}{}^\gamma(x)\delta^{(3)}(\vec{x}-\vec{y})], \tag{3}$$

where $\mathfrak{F}_0{}^\gamma$ is the isospin current. Since these commutators [especially the one given in Eq. (2)] have been used in a large number of places some far-reaching consequences are expected.

(2) The Adler neutrino sum rule[4] is modified, the new one being given by

$$\int_0^\infty [W_2^{\bar{\nu}}(\nu, q^2) - W_2^{\nu}(\nu, q^2)]\, \nu^{-1}\, d\nu = [2 - (\beta^2/4M^2)q^2] \cos^2\theta_c, \qquad (4)$$

where, $W_2^{\nu,\bar{\nu}}$ are the well-known structure functions appearing in the deep inelastic neutrino scattering. Because of the presence of the q^2 term on the right-hand side, this sum rule is not consistent with the scaling of $W_2^{\nu,\bar{\nu}}$. This has to be contrasted with the various charm schemes[5] where the alteration of the Adler sum rule is such that it is still consistent[6] with the scaling of $W_2^{\nu,\bar{\nu}}$. It may be hoped that the data around $q^2 = 50$ GeV^2 may be able to decide between the paracharge and other models.

(3) The charge-density commutator which is usually believed to be zero is now not so and is given by[7]

$$[\rho(x), \rho(y)]_{x_0 = y_0} = \tfrac{2}{3} i (\beta^2/4M^2) \epsilon_{lmn} \partial_l^{\,x} \partial_m^{\,y} [A_n^{\,3}(x) \delta^{(3)}(\vec{x} - \vec{y})]. \qquad (5)$$

In view of the above modification of this commutator, the Drell-Hearn-Gerasimov sum rule[8] (say for the proton) will be altered as follows:

$$(K_p/2M_p)^2 + (8\pi^2\alpha)^{-1} \int_0^\infty [\sigma_p(\nu) - \sigma_A(\nu)]\, \nu^{-1}\, d\nu = (\beta^2/12M^2) g_A(0), \qquad (6)$$

so that there must exist a fixed pole in the spin-flip Compton scattering.[9] Obviously, the Cabibbo-Radicati sum rule[10] will also be modified.

(4) In view of the modified commutator (3), Fubini *et al.*'s low-energy theorems[11] for neutral-pion photoproduction will need alteration. Similarly, the superconvergence sum rule for charged-pion photoproduction[12] will be modified to the extent that a fixed pole would occur in charged-pion photoproduction.

(5) In view of the above modifications, one can set an upper bound on the possible values of the quark anomalous magnetic moment $\beta/2M$. In fact, the Drell-Hearn-Gerasimov and Cabibbo-Radicati sum rules have been so well tested that they fix $|\beta|/2M < 0.1$ GeV^{-1}. It is interesting to note that Das *et al.*'s rough estimate of 0.08 GeV^{-1} is below and very close to the upper bound.

(6) Since the space components of the vector current are also altered, modifications in the Schwinger-term sum rule, the Callan-Gross relation, etc., are also expected.

Finally, in view of the above anomalous vector current one should also modify the axial-vector current. Such an anomalous vector current should have the form

$$[A_\mu^{\,i}(x)]_{\text{anom}} = i(\beta'/2M)\partial[\bar{\xi}(x)\sigma_{\mu\nu}\gamma_5 \tfrac{1}{2}\lambda^i \xi(x)]/\partial x_\nu. \qquad (7)$$

It is amusing that this anomalous piece is nothing but the second-class axial-vector current whose presence has been indicated[13] by the large asymmetry in *ft* values of the mirror nuclei. The consequences of such a current have already been studied by the author.[14] Needless to say, Adler's neutrino sum rule is further modified.

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Slope of ψ Regge Trajectories and a Test of "Elementarity" of the ψ Particles in 2ψ Production by Hadrons*

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If the ψ particles are not Reggeons, the cross section for 2ψ production would rise to $\sim 10^{-32}$ cm^2 in high-energy hadron-hadron collisions. This is based on the observed photoproduction of a single ψ.

It is currently fashionable to assume the ψ particles[1,2] to be loosely bound states of a quark and an antiquark of a new quantum number, in particular, charm.[3] This is the most attractive model presently discussed by theorists since it can accommodate both the unified gauge theory of weak and electromagnetic interactions[4] and asymptotic freedom of strong interactions.[5] In the charm model with color gluons the potential is given by a Coulomb force plus a confining force at a long distance, so that a few charm-anticharm bound states of positive charge conjugation should exist most naturally below the first exited state (3.7 GeV) of $^3S_1$.[6] However, no monochromatic γ rays have so far been observed from the $\psi(3.7)$ at SPEAR.[7] Another problem is that in spite of an apparent threshold behavior at 3.8–4.2 GeV in e^+e^- collisions, no charmed mesons have yet been found in the invariant-mass plot of either strange mesons or nonstrange mesons.[7] Although these results have not yet been established at all firmly, it would not be absurd to give a little thought to the possibility that the ψ particles might be "elementary." By the word "elementary," I mean not only that the ψ particles at 3.1 and 3.7 GeV need not imply the existence of more of new states such as ψ of positive charge conjugation or charmed mesons, but also that the ψ particles may not lie on a Regge trajectory of a normal slope.

Very recently, photoproduction of a single ψ has been observed.[8] Assuming that the production is diffractive, one can estimate that the total ψN cross section is about 1 mb at high energies. Given this number, one can test experimentally whether the ψ particles are Reggeons or not. One of the processes most suitable for this purpose is

$$N + N \to N + \psi + N + \psi \tag{1}$$

at small momentum transfers between the initial nucleon and the final $(N\psi)$. The ψ particles can be exchanged as shown in Fig. 1. The Pomeranchukon and ordinary Reggeons can be exchanged, too, but according to the narrow hadronic decay widths of $\psi(3.1)$ and $\psi(3.7)$ and also to the ψ production in the p-Be reaction[2] the process

$$(P \text{ or } R) + N \to N + \psi \tag{2}$$

is expected to be suppressed by a factor of $\sim 10^{-5}$ as compared with $(P$ or $R) + N \to N +$ (ordinary meson). The production cross section of 2ψ through P or R exchange would therefore be $\sim (10^{-5})^2 \times (10 \text{ mb}) = 10^{-36}$ cm^2. If the ψ particles are elementary or, equivalently, lie on a flat trajectory, however, the ψ exchange would dominate completely in the process (1). It is the purpose of this short note to give an estimate of the 2ψ production through one-ψ exchange and to discuss its implications.

2ψ production through elementary ψ exchange.—The production amplitude is given by

$$M = i(2\pi)^4\delta(p + p' - k_1 - p_1 - k_2 - p_2)\left\{-g^{\mu\nu} + \frac{(p_1 + k_1 - p)^\mu (p_1 + k_1 - p)^\nu}{m_\psi^2}\right\}\frac{1}{m_\psi^2 - t} \times \langle\psi(k_1)N(p_1)|J_\mu(0)|N(p)\rangle\langle\psi(k_2)N(p_2)|J_\nu(0)|N(p')\rangle, \tag{3}$$