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The Weak Charges of Charmed Particles

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The ψ particles discovered in e^+e^- production [1] and annihilation[2] are now interpreted as compound states of a charmed quark and its charge conjugate.[3] A definite support to this interpretation follows from the discovery[4] of new states of opposite charge conjugation. Since the highest ψ particle[2] found up to now has a rather large width compared to the others two, it is reasonable to think that it decays into a pair of charmed particles (like $\phi \rightarrow K\overline{K}$); so one gets an idea about the mass of the lowest charmed state. The opeining of the threshold for the production of charmed particles should imply a fast increase of the ratio R, which is indeed observed. Therefore one would expect to find charmed particles just above the region where R changes: in fact the $e^{\pm}\mu^{\mp}$ events found in e^+e^- reaction at that energy give a signal for the existence of a new particle;[5] however the final leptons spectrum indicates a three-body decay of the new particle, which therefore rather behaves like a new lepton (remember that while $\mu^- \rightarrow e^- + \nu_\mu + \overline{\nu}_e$ the main decay of π^- is the two body decay $\mu^- + \overline{\nu}_\mu$).

Anyway the existence of a new lepton is not at all disappointing since it would simulate a growth of one unity for R, which is welcome since the opening of the charm threshold by itself is not enough to explain the increase in the product S^2 in (e^+e^-).

While in e^+e^- annihilation the discovery of the ψ particles has not been accompanied by the detection of charmed particles, there are good reasons to believe that these particles are produced in neutrino and antineutrino reactions;[6] in fact the interpretation of the two muon events in terms of a new hadron is the most convincing; the event with apparent violation $\Delta Q = \Delta S$ rule ($\nu_\mu + p \to \mu^- \Lambda \pi^+ \pi^+ \pi^+ \pi^-$) could be rather well interpreted as due to the production of a charmed particle followed by a non-leptonic decay.

The most convincing support to the idea that charmed particles are produced are the three $\mu^- e^+$ events with associated strange particle production detected in the Gargamelle exposure to the neutrino beam of CERN.

The existence of a fourth quark, already conjectured many years ago in analogy with leptons,[7] is not unexpected, since it has been advocated[8] in connection with the current - current lagrangian of weak interactions; there it has been shown the usefulness of introducing a new quark, with the same charge of p_0, coupled by the weak charged current to the combination $-\sin\theta_c n_0 + \cos\theta_c \lambda_0$, which is orthogonal to the one coupled to p_0 according to the theory of Cabibbo. The high value of the mass of the ψ particle, compared to the other 1^- vector mesons, is a clear hint that the SU(4) symmetry is strongly broken.

The purpose of this letter is to give an expression of the vector and axial vector charges of hadrons, with particular attention to charmed particles, generalizing to SU(4) the considerations developed in a previous work[9] for the weak charges in broken SU(3). As in ref. 9 one assumes that the vector charges Q^i (i = 1...15) and the axial vector charges Q_5^i are connected, at $P_z = \infty$, to the corresponding generators of the classification group $A\left(\frac{\mu_i}{2}\right)$ and $A\left(\frac{\mu_i \sigma_z}{2}\right)$ by a unitary transformation V.

Here one assumes that the operator V acts on a system of quarks as the product of a set of commuting unitary operators acting on a single quark[10]: this hypothesis implies definite transformation properties of the axial charges with respect to the classification group, whose consequences have been successfully compared with experiment.[11, 12]

The V operator acts on a single quark as:

$$\begin{aligned} V q_i^{\uparrow}(\vec{K}, X) &= \cos\hat{\theta}_i(\vec{K}, X) q_i^{\uparrow} + \frac{K_x + iK_y}{K_\perp} \sin\hat{\theta}_i(\vec{K}, X) q_i^{\downarrow} \\ V q_i^{\downarrow}(\vec{K}, X) &= \cos\hat{\theta}_i(\vec{K}, X) q_i^{\downarrow} - \frac{K_x - iK_y}{K_\perp} \sin\hat{\theta}_i(\vec{K}, X) q_i^{\uparrow} \end{aligned} \tag{1}$$

The diagonal vector charges (T_3, Y, C) are not renormalized, since V does not change the internal quantum numbers of the quarks. Conversely the corresponding axial charges have their matrix elements renormalized by a factor

$$\cos^2\hat{\theta}_i - \sin^2\hat{\theta}_i = \cos 2\hat{\theta}_i \tag{2}$$

(the term which flips the spin of the quark is not considered here for simplicity, since one is interested only in states with s-wave quark, the 63 of mesons and the 120 of baryons).

Conversely the non-diagonal vector and axial vector charges are both renormalized respectively by the factors

$$\cos \hat{\theta}_i \cos \hat{\theta}_j \pm \sin \hat{\theta}_i \sin \hat{\theta}_j = \cos (\hat{\theta}_i \mp \hat{\theta}_j) \tag{3}$$

In conclusion the matrix elements of the charges concerning the lowest meson and baryon multiplets of SU(8) are proportional to the corresponding generators of the same algebra by an amount characteristic of each charge. For ordinary hadrons this ansatz has worked reasonably well in connecting the different effects of SU(3) breaking on the semi-leptonic decays of the baryon octet:[9] in particular a different renormalization factor for the strangeness changing and strangeness conserving axial charges has practically the same effect as introducing two different angles for the Cabibbo rotation of the vector and axial vector weak currents.

If one considers the strangeness changing decays of pseudoscalar charmed particles,[13] one has:

$$\frac{\langle \eta | Q^{13+i14} | F^+ \rangle}{\langle X^0 | Q^{13+i14} | F^+ \rangle} = \frac{-\sqrt{2} + tg\theta_p}{1 + \sqrt{2}\, tg\theta_p} \tag{4}$$

where θ_p is the mixing angle for the pseudoscalar nonet, and the decay

$$F^+ \rightarrow \omega + e^+ + \nu_e$$

is forbidden. For the strangeness conserving decays (which anyway are expected to be depressed by a factor $\sim tg^2\theta_c{}^8$ with respect to the previous ones):

$$<\pi^0 |Q^{11+i12}| D^+> : <\eta | Q^{11+i12} | D^+>:$$

$$: <X^0 | Q^{11+i12} | D^+> = 1 : \frac{1}{\sqrt{3}} (\cos\theta_p + \sqrt{2}\sin\theta_p): \qquad (5)$$

$$: \frac{1}{\sqrt{3}} (\sqrt{2}\cos\theta_p - \sin\theta_p)$$

while the decay

$$D^+ \rightarrow \phi + e^+ + \nu_e$$

is forbidden and

$$<\rho^0 |Q_5{}^{11+i12}| D^+> = - <\omega| Q_5{}^{11+i12} | D^+> \qquad (6)$$

For the strong decays of the charmed particles into a pion plus another charmed particle one predicts the same coupling constants obtained with the strange quark in place of the charmed one:

$$<D^{*+} |Q_5{}^3| D^+> = \overline{<K^{*0}} |Q_5{}^3 |\overline{K^0}> \qquad (7)$$

Of course the $\rho\pi$ decay of the ψ particle is forbidden, as $\langle\psi|Q_5^3|\rho^0\rangle = 0$. In a similar way all the matrix elements of the charge Q_5^3 between the $20, \frac{1}{2}^+$ and $20, \frac{3}{2}^+$ states of the $\underline{120}$ of SU(8) are all given in terms of one parameter, which is anyway already known from the matrix elements concerning ordinary hadrons.

An extension of P. C. A. C. to caons allows one to obtain from $\langle F^{*+}|Q_5^{6-i7}|D^+\rangle = -\langle D^{*+}|Q_5^{6+i7}|F^+\rangle$ the corresponding equality for the amplitudes for

$$F^{*+} \to D^+ + K^0 \text{ and } D^{*+} \to F^+ + \overline{K^0}$$

More in general all the emission of caons within states of the $\underline{63}$ and $\underline{120}$ are obtained in terms of only one parameter given by $K^* \to K + \pi$ (a priori there should be one parameter for each representation, but the quark universality allows to rely mesons and baryons).

To get a quantitative idea of the renormalization parameters involved it is appropriate to use the phenomenological information available about the V operator.

From a model independent analysis[14] of the chiral wave function of the baryon octet one learns that the most important representations of SU(3) $\otimes$ SU(3) are the $(6, 3)_8$, the $(3, \overline{3})_8$ and the (8, 1) with decreasing weight (this result is obtained on the hypothesis that the chiral algebra is saturated within non exotic states; this hypothesis anyway is true if V, like here, does not change the number of quarks): the

(6, 3) is the $S_z = \frac{1}{2}$ part of the 56, while the (3, 3) and the (8, 1) with $J_z = \frac{1}{2}$ stay in the 70,L = 1 with $L_z = \pm 1$. This pattern is well-reproduced by the Z operator introduced in ref. 15, which connects the 56, L = 0 to the states $L_z = \pm 1$ of the 70,L = 1. The property $\Delta L_z = \pm 1$ of z supplies a natural explanation for the dominance of the term with the same property[16, 12] in the decays of the baryons of the 70, L = 1 into 56 plus a pion. Finally the Z operator accounts very well for the decays of the mesons of the 35 L = 1 into 35 plus a pion: moreover, as it has also been stressed in Ref. 15, a universal behavior of quarks in baryons and mesons appears: in fact G_A/G_V and the $\pi - \rho$ coupling constant are renormalized by the same amount with the respect to the value when V = 1.

In ref. 9 by considering only the 56 and the 70 $L_z = \pm 1$ in the chiral wave function of the octet, one has been able to obtain the renormalization factor for the strangeness violating vector charge in terms of the ones concerning the axial charges. In the formalism of this letter one can write:

$$V q_i^{\uparrow} |\text{ground state}\rangle = \cos\theta_i q_i^{\uparrow} |\text{ground state}\rangle + \sin\theta_i q_i^{\downarrow} | L_z = +1\rangle \qquad (8)$$

$$V q_i^{\downarrow} |\text{ground state}\rangle = \cos\theta_i q_i^{\downarrow} |\text{ground state}\rangle + \sin\theta_i q_i^{\uparrow} | L_z = -1\rangle$$

where now the θ_i's are <u>numbers</u> and the state $|L_z = \pm 1\rangle$ <u>is the same</u> for each quark. (For a single quark this hypothesis is still saved, since their mixing is smaller than the total one.) It is easy to deduce that the vector and axial vector charges come out to be renormalized respectively by the factors $\cos(\theta_i \mp \theta_j)$ where i and j are the quarks concerned by the matrix element.

The mixing angles of the ordinary quarks can be obtained by the previous fit:[9]

$$\theta_{p_0} = \theta_{n_0} \cong 20^{\circ}$$
$$\theta_{\lambda_0} \cong 28^{\circ} \qquad (9)$$

So all the matrix elements of the charm changing charges may be written in terms of the mixing angle θ_{c_0}. To determine θ_{c_0} one may assume that also for charmed particles the matrix elements of the magnetic moment are proportional to the ones of the axial charges: for the baryon octet such a hypothesis leads to the famous ratio $-2/3$ for μ_n/μ_p and is also rather successful in predicting the Λ and Σ^+ magnetic moments.[9] Generalizing to the inclusion of the charmed quark the considerations developed for the three other ones, one can write the magnetic moment operator as:

$$\vec{M} = \mu_0\Big(\frac{2}{3}\cos 2\theta_{p_0}\vec{S}_{p_0} - \frac{1}{3}\cos 2\theta_{n_0}\vec{S}_{n_0}$$

$$- \frac{1}{3}\cos 2\theta_{\lambda_0}\vec{S}_{\lambda_0} + \frac{2}{3}\cos 2\theta_{c_0}\vec{S}_{c_0}\Big) .$$

The equation just written relates the angle θ_{c_0} to the decay rate $\Gamma(\psi \to \eta_c + \gamma)$. Despite the fact that there is not even yet definite evidence for the existence of η_c particle, the measured branching ratio (1.5×10^{-4})[17] for the chain

$$\psi \to \eta_c(2800) + \gamma$$
$$\hookrightarrow \gamma + \gamma$$

requires, with reasonable assumptions on the η_c decays,[18] that the magnetic moment of the charmed quark is very small compared to the ordinary quarks; this implies $\cos 2\theta_{c_0} \cong 0$ and therefore:

$$\theta_{c_0} \cong 45^\circ \tag{11}$$

From this value one can compute all the weak charges with $\Delta C = 1$:

$$<K^-|Q^{13+i14}|D^0> = \frac{1}{-\frac{2}{\sqrt{3}}\cos\theta_p + \frac{1}{\sqrt{3}}\sin\theta_p} = -1.12$$

$$<\eta|Q^{13+i14}|F^+> = \cos 17^\circ = .96 \tag{12}$$

$$<\overline{K^{*0}}|Q_5^{13+i14}|D^+> = <\phi|Q_5^{13+i14}|F^+> = \cos 73^\circ = .29$$

$$<\pi^- | Q^{11 + i12} | D^0> \; = \; <K^0 | Q^{11 = i12} | F^+> \; = \; \cos 25^{\circ} \; = \; .91$$

$$-\sqrt{2} <\rho^0 | Q_5^{11 + i12} | D^+> \; = \; <K^{*0} | Q_5^{11 + i12} | F^+> \; = \; \cos 65^{\circ} \; = \; .42$$

It is somehow disappointing, in view of the current interpretation[19] of the operator V in terms of the relativistic motion of quarks inside the hadrons, that the charmed quark, which is heavier, is more mixed than the ordinary ones; anyway such unexpected behavior has already been found for the strange quark[9] in order to explain the experimental fact that the S = 1 axial charge seems to have a slightly smaller renormalization factor than the S = 0. The weak charges of the baryons are renormalized by the same amount in view of the universality properties showed up by the V operator; but, before discussing them in detail, it is wise to wait and see if the charmed baryons have a mass sufficiently high to decay strongly into an ordinary baryon plus a charmed meson. Despite the fact that the mixing effects discussed here are relevant also for the leptonic decays of the D and F particles, the presence of the a priori unknown constants f_D and f_F does not allow us to make unambiguous predictions.

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