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Paracharge phenomenology: systematics of the new hadrons

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Abstract. A systematic semiquantitative account of all aspects of the strong and electromagnetic interactions of all the newly discovered hadronic states (the ψ's, the χ's, etc.) is presented within the framework of the paracharge scheme. Extensions of ideas familiar from the SU_3 classification scheme to SU_4 are shown to provide an understanding of the new states seen in the decays of $\psi(3.1)$ and $\psi'(3.7)$, including their masses and gross decay characteristics. The decays of $\psi(3.1)$ and $\psi'(3.7)$ themselves are studied in some detail. Since these are of electromagnetic origin in the scheme, their electromagnetic mixing with the resonance at 4·15 GeV (the P-state of the scheme) is important. Once this is taken into account, the resulting picture is in excellent agreement with available data.

Keywords. ψ-particles; SU_4 symmetry; paracharge; anomalous currents; new hadrons; e^+e^- annihilation.

1. Introduction

In the year since the two narrow resonances, the $\psi(3.1)$ and the $\psi'(3.7)$, were discovered, an enormous amount of data directly relating to them has accumulated, the highlights being, (i) the detailed study of the decays of $\psi(3.1)$ and, less extensively of $\psi'(3.7)$; (ii) the discovery of more resonances in the $e\bar{e}$ system; (iii) the discovery of resonances in the decay products of $\psi(3.1)$ and $\psi'(3.7)$; and (iv) the measurement of $R=\sigma(e\bar{e}\rightarrow \text{hadrons})/\sigma(e\bar{e}\rightarrow\mu\bar{\mu})$ up to $E_{CM}\simeq 7.5$ GeV. It would appear that, together, all this information is sufficient for at least a preliminary attempt at assessing the merits of theoretical pictures of these phenomena. In this paper, we do this for the paracharge scheme, a scheme which we proposed (Das *et al* 1975 *a*, 1975 *b*)* in a preliminary version in the early days of the new hadronic physics. It will be seen that the model provides a very satisfactory unified picture of all the aspects listed above of the phenomena directly related to the new hadrons. Not surprisingly, our considerations are at this stage necessarily of a semiquantitave nature—it is clearly too early for detailed dynamical calculations.

The paracharge scheme is an SU_4 classification scheme for hadrons, devised to accommodate the two narrow hadronic resonances, the $\psi(3.1)$ and the $\psi'(3.7)$, into two $(15\oplus 1)$-plets of vector mesons containing the ρ and the ρ' respectively

* We refer to this work as I in the present paper.

(the new additive quantum number is the paracharge, Z). The additional members of the 16-plet containing the ψ, *e.g.*, are an SU_3 triplet ($D^{+,0}$ with $I=\frac{1}{2}$, $Y=1$, $Z=-1$; S^0 with $I=Y=0$, $Z=-1$), the corresponding antitriplet (D^-, $\bar{D}^0$, $\bar{S}^0$) and a neutral SU_3 singlet (P) with $Y=Z=0$. The $\psi(3.1)$ is the $C=-$linear combination $S_-^0 \equiv (S^0-\bar{S}^0)/\sqrt{2}$. The $\psi'(3.7)$ is correspondingly denoted by $S_-^{0\prime}$. The hadronic electromagnetic current in this scheme consists of the Dirac current of the quarks, $\mathcal{F}_\mu^{em}$, as well as a new chargeless, Pauli part $\mathcal{G}_\mu^{em}$ which has SU_4 components $\mathcal{G}_\mu^{\Delta Z}$ that change Z by ± 1. It is this latter current which is responsible for the production and decay of the ψ (3.1) as well as for the production and an important fraction of the decays of the ψ' (3.7). Z is strictly conserved in strong interactions.

In the next section we discuss the classification and properties of the new resonances, focussing on those discovered more recently. Section 3 is devoted to the decays of ψ (3.1) and ψ' (3.7). The main conclusion here, apart from a generally satisfactory picture of the decay patterns is that some decay features which are considered puzzling, such as the value of the ratio $\mathrm{Br}[\psi(3.1)\rightarrow\phi\pi^+\pi^-]/\mathrm{Br}[\psi(3.1)\rightarrow\omega\pi^+\pi^-)$ and the apparent validity of G-conservation in the hadronic decays of ψ (3.1), but not of ψ' (3.7) are very naturally accounted for in the paracharge scheme (Das *et al* 1975 *d*). Section 4 provides some general remarks concerning the properties of the new hadronic current that is a part of the model.

It is to be stressed here that our only concern in this paper is a phenomenological description in as natural and economic a way as possible of the many aspects of the interactions of the newly discovered hadrons. More fundamental questions about the nature of the Pauli quark-current, its dynamical origin or the possible non-renormalizability of its coupling to hadrons are not touched upon.

Also excluded from discussion are the other exciting recent developments, namely, the production of dileptons in neutrino-hadron interactions and in $e\bar{e}$ collisions as well as the anomalous cosmic ray neutrino interactions. In a comprehensive picture of strong, electro-magnetic and weak interactions which we are now developing on the basis of the paracharge scheme, these new phenomena are only indirectly related to the properties of paracharged *hadrons* and their explanation is to be sought in a generalisation of the theory of weak interactions.

2. Quantum number assignments for the new particles

2.1. *Completion of the ψ and ψ' multiplets*

The basic quartet of quarks of the paracharge model consists of the usual SU_3-triplet (p, n, λ) and the SU_3-singlet quark χ with paracharge $Z=1$, hypercharge $Y=-2/3$ and charge $Q=-1/3$. The ψ is then, in quark language, the state $S_-^0 \equiv (|\bar{\chi}\lambda\rangle - |\bar{\lambda}\chi\rangle)/\sqrt{2}$; thus, unlike in charm models, the ψ is not a state with the new quantum number "hidden" and its relative stability does not have to invoke a poorly understood concept such as extreme purity of the wave function. Consequently, it was predicted in I that the "hidden paracharge" state P, which for the ideal mixing case would be mostly $|\chi\bar{\chi}\rangle$, should be seen in $e\bar{e}$ annihilation experiments with a width (due to impurities in the wave function) of a few hundred MeV extrapolating from the decay of ϕ to $\rho\pi$. An application of the (approximate) ideal-mixing mass formula gave the masses of P [corresponding to

ψ (3.1)] and P' [corresponding to ψ' (3.7)] as $m(P) \simeq 4.3$ GeV and $m(P') \simeq$ 5 GeV. Almost simultaneously, a spectacular peak was observed (Augustin *et al* 1975) in σ ($e\bar{e} \to$ hadrons) at $\sqrt{s} = 4.15$, with a width of ~200–250 MeV. It is natural for us to identify this as a *genuine resonance*, the P. As for the P', later measurements of σ ($e\bar{e} \to$ hadrons) [reported by Feldman and Perl (1975) (see especially figure 43 (*a*) and tables 4 and 17)] showed a smaller and broader bump at $\sqrt{s} \simeq 4.9$ GeV. The most recent data (Schwitters 1975) however have many more points around this energy, all with much larger errors, making the identification of a possible structure harder. It was expected that the P' would be much broader than the P (4.1). Because of this the experimental identification of the P' may be much harder just as the ρ' has been harder to establish them the ρ.

The paracharged, hypercharged vector mesons, the $D^{\pm}$ D° and $\bar{D}^0$, remain to be seen. Confining ourselves to the radial ground states (the partners of the ρ, ω, ϕ, ψ), they are predicted to have a mass in the same region as $m(\psi)$, and the most promising way of looking for them is in the decay products of ψ' (3.7) (see the last section). As for the $S_+{}^0$, the even charge conjugation partner of ψ with a very nearly degenerate mass, its detection is likely to be extremely difficult.

2·2. *A second radial excitation*?

The most recent data (Schwitters 1975) show yet another clear peak at $\sqrt{s} \simeq$ 4·5 GeV, with a width of the order of 50 MeV. We identify this as the second radial excitation, in the $q\bar{q}$ picture, of the ψ (3·1). To understand the reasons for our suggestion that we are actually seeing here a second excitation, it is useful to recall that within the paracharge model the ψ' (3·7) is interpreted (as in some other models) as the first radial excitation of ψ (3·1). The total width Γ (ψ') then is made up of two components, $\Gamma_{\rm st}$ (ψ') arising from *strong*, paracharge conserving decays and $\Gamma_{\rm em}$ (ψ'), made up of electromagnetic decays into both paraneutral and paracharged hadrons, with the possible emission of a photon. From the measured branching ratio (Abrams *et al* 1975) Br ($\psi' \to \psi +$ anything) $\simeq 57\%$, we know that $\Gamma_{\rm st}$ (ψ') > 130 KeV (there are other paracharged channels into which ψ' can decay). In fact, but for the inhibiting influence of a PCAC suppression, this branching ratio is expected to be even larger (Callan *et al* 1975; Pasupathy 1974).

The fact that the only strong decays of paracharged particles are into high mass states involving lower lying paracharged particles implies a dramatic change in their widths as their masses increase. Thus while $\Gamma_{\rm st}$ (ψ) is negligible, $\Gamma_{\rm st}$ (ψ') is a major fraction of the total width. The second radial excitation of ψ can then be expected to have a width which is a few order of magnitude larger than that of the first excitation, ψ', because of the larger number of paracharged channels available and because of the larger Q-values whose most significant impact will be to counteract the Adler-zero suppression. At the same time, the width will not be so large as to swamp the peak, since all low-lying ($Z = 0$) hadronic channels are inaccessible except electromagnetically. The electro-magnetic width as well as the production rate of ψ'' in $e\bar{e}$ collisions are expected to be more or less the same as for ψ and ψ'. In the light of these remarks, the position and the width of the 4·5 GeV peak are roughly what will be expected of the second excitation. Obviously, in the case of paraneutral, " ordinary ", vector mesons, the search and identification of a second radial excitation (*e.g.*, ρ'', P'') will remain a difficult matter.*

2.3. *Other multiplets*

We expect of course, as stated in I the completion of other known meson multiplets through the discovery of their paracharged and "hidden-paracharge" partners. All the newly found resonances in the decays of ψ and ψ' fit in quite well with this expectation, including their masses and what little is known of their decay properties. Thus, mass formulae pertaining to non-relativistic SU_8 lead to a value $m\,(S\,(PS)) \simeq 2.9$ GeV for the mass of the pseudoscalar partners of the ψ (3.1) and of these the even charge conjugation states S_+^0 (PS) is accessible to ψ *via* the electromagnetic current (*see* I). Such a state, at a mass $\simeq 2.8$ GeV has recently been observed through its 2γ decay mode (Wiik 1975). The discrepancy in masses is not surprising in view of the *a priori* approximate nature of SU_8 mass formulae. The more reliable SU_4 mass formula without any mixing (the pseudoscalars being far from maximally mixed) then gives $m\,[P\,(PS)] \simeq$ 3.5 GeV. This is an ideal slot for χ (3.53), one of the three so called intermediate states (Braunschweig *et al* 1975; Feldman *et al* 1975, Feldman 1975 *b*) found in ψ' decays. The facts that it is broad and that it does not decay into two pseudoscalars are entirely consistent with this assignment. Mass formulae (perhaps very approximate) expressing angular momentum independence also give for the $J^P = 2^+$ and 1^+ counter parts respectively of ψ, $m\,(S\,(T)) \simeq 3.3$–3.4 GeV, $m\,(S\,(A)) \simeq 3.2$–3.3 GeV. It is natural for us to identify the even charge conjugation combinations of these states, namely S_+^0 (T) and S_+^0, (A), as the χ (3.41) and as the P_c (3.27) respectively. The relative narrowness of these states and the natural parity of χ (3.41) are in favour of this identification.

These assignments are very tentative and are given here simply to point out that the scheme has place for intermediate states. We must await detailed experimental information on these states before making firm assignments.

We may note here that the ψ' (3.7) cannot decay strongly into $S_\pm$ (T) or $S_\pm$ (A) with the emission of one pion (I-spin conservation) nor into S_+ (T), S_+ (A) with the emission of two pions (parity and charge conjugation invariance together with Bose statistics for pions). But the decays into the corresponding negative charge conjugation states and two pions are possible, with the 2 pions in a relative S wave and their centre of mass in a P wave with respect to the S_-. The resulting angular momentum suppression will also be reinforced by the reduction in phase space (when compared to the decay $\psi' \to \psi + 2\pi$) and even more significantly by the nearness of the PCAC zero. Thus we expect such decays to be present, but with a considerably smaller branching ratio than $\mathrm{Br}(\psi' \to \psi + 2\pi)$. Since the even and odd charge conjugation states are degenerate for the present purpose, these decays will appear as peaks in the missing mass spectrum in $\psi' \to 2\pi +$ anything, at $m = 3.27$ and 3.41 GeV respectively. It is needless to say that, because of the expected smallness of the widths, high statistics will be required to identify these peaks—conditions not met by the data publsihed so far (Abrams *et al* 1975).

* There are indeed indications of a possible ρ''; see, e.g. Alles-Borelli *et al* (1975) and references contained therein.

We may emphasize here that there is room for extra intermediate states purely from conventional broken symmetry consideration in as much as all known SU_3 multiplets have now to be extended to SU_4 multiplets. They do not necessarily require any Coulomb like potential models.

3. Decay properties

3.1. *General features of* ψ *and* ψ' *decays*

All decays of the ψ (3.1) and a major part of the decays of the ψ' (3.7) are electromagnetic in our model. Therefore their electromagnetic mixing with neighbouring states will play a significant role in their decays, a point overlooked in I. Especially important will be the mixing, through the intervention of the Z-charging Pauli current $\mathcal{G}_\mu{}^{\Delta z}$, of these states with the P, on account of the large value of $\Gamma(P)$. Focussing on the ψ for illustration, we write

$$|\psi\rangle = |S_-^\circ\rangle \cos\lambda + |P\rangle \sin\lambda$$

and have, for any final ($Z = 0$ hadronic) state $|f\rangle$,

$$|\langle f|S|\psi\rangle|^2 = \cos^2\lambda\,|\langle f|S|S_-^\circ\rangle|^2 + \sin^2\lambda\,|\langle f|S|P\rangle|^2$$
$$+\, 2\mathrm{Re}\cos\lambda\sin\lambda\,\langle P|S^+|f\rangle\langle f|S|S_-^0\rangle,$$

where S is the S-matrix. Each of the terms on the right is of order α^2, since $\lambda \sim \alpha$ and $\langle f|S|S_-^0\rangle$ is also $\sim\alpha$, while $\langle f|S|P\rangle \sim 1$. We note that in the total width, the interference term does not contribute because

$$\sum_f \langle P|S^+|f\rangle\langle f|S|S_-^0\rangle = \langle P|S^+S|S_-^0\rangle = 0.$$

We may therefore write (Γ_h stands for the hadronic width)

$$\Gamma_h(\psi) = \Gamma'_h(\psi) + \Gamma''_h(\psi),$$

with $\Gamma'_h(\psi) \equiv \cos^2\lambda\Gamma_h(S_-^0)$ and $\Gamma''_h(\psi) \equiv \sin^2\lambda\Gamma_h(P)$. Though the mixing angle will be small, the very large value of $\Gamma_h(P)/\Gamma_h(S^\circ_-) \simeq 10^4$ can (and in fact does, as we shall soon see) make $\Gamma_h''(\psi)$ comparable with or even larger than $\Gamma'_h(\psi)$. For exclusive decay channels we have only the inequality

$$\Gamma(\psi \to f) \leqslant 2\,[\Gamma'(\psi\to f) + \Gamma''(\psi\to f)],$$
$$\Gamma'(\psi\to f) = \cos^2\lambda\,\Gamma(S_-^0\to f),\ \Gamma''(\psi\to f) = \sin^2\lambda\Gamma(P\to f).$$

Nevertheless, very occasionally we shall take $\Gamma(\psi\to f) \simeq \Gamma'(\psi\to f) + \Gamma''(\psi\to f)$ understanding that the corrections from the interference term will not greatly affect the semiquantitative nature of our estimates. The important points is that Γ'_h, which arises from the S^0_- decays follows selection rules governing electromagnetic decays, while Γ''_h, which comes from the P admixture, describes decays which respect all strong interaction selection rules.

Our approach to the understanding of why ψ (3.1) is such a sharp resonance is thus fundamentally different from the popular charm scheme, which relies on the extreme purity of the hidden charm state that is ψ for the same purpose. We therefore think it appropriate to give here a line of reasoning which convinces us that such a high degree of purity is unlikely to govern the quark wave functions of the ψ. In a picture in which ideal mixing of the neutral states in an SU_4 $\underline{15}$ plet is responsible for the purity of the wave function, it follows that ϕ must in turn have an equally pure $\lambda\bar{\lambda}$ wave function, in which case the non-negligible value of the branching ratio Br $(\phi \to \rho\pi)$ ($\simeq$ 16%) must arise from rescattering of the dominant $K\bar{K}$ final state into $\rho\pi$ (Pasupathy 1975). If this is so, it is possible to derive a unitarity upper bound on $\Gamma'(\phi)$, the width of ϕ into all states *excluding* the $K\bar{K}$ state. If A is the $J = 1$ partial wave " T-matrix ", and ignoring inessential common factors, unitarity tells us that

$$\mathrm{Im}\,\langle x \mid A \mid \phi\rangle = \sum_n \langle n \mid A \mid x\rangle \langle n \mid A \mid \phi\rangle$$

so that

$$\Gamma'(\phi) = \sum_{x \neq K\bar{K}} \Big|\sum_n \langle n \mid A \mid x\rangle \langle n \mid A \mid \phi\rangle\Big|^2$$

$$= \sum_{x \neq K\bar{K}} \big|\langle K\bar{K} \mid A \mid x\rangle \langle K\bar{K} \mid A \mid \phi\rangle\big|^2$$

$$= \Gamma(\phi \to K\bar{K})\,(\mathrm{Im}\,a - |a|^2),$$

where a is the $J = 1$ $K\bar{K} \to K\bar{K}$ partial wave amplitude. The second factor on the right is bounded above by 1/4, so that we have

$$\Gamma'(\phi) \leqslant \tfrac{1}{4}\,\Gamma(\phi \to K\bar{K}).$$

In deriving this bound, we have saturated the sum over n by the dominant $K\bar{K}$ state; this can be corrected for by iteration with essentially no change in the bound. Experimentally, the situation is that $\Gamma'(\phi)$ is almost exactly (1/4) $\Gamma(\phi \to K\bar{K})$. It is easy to see that this experimentally observed saturation is possible *only* if $a = i/2$, which requires a high degree of inelasticity in the $K\bar{K}$ elastic amplitude at this low energy. This, we feel is rather unlikely, leading us to the conclusion that the ρ decay mode of ϕ cannot arise entirely from rescattering corrections.

A second general topic of relevance here is connected with the fact that decays ψ and ψ' into a small number of light particles (including the photon) appear to be inhibited. While nothing like a basic understanding of this effect is as yet available, there is now wide recognition of a number of qualitative mechanisms suppressing such decays: (i) If the decay matrix element is assumed to be independent of the number n of (light, relativistic) final state particles, the value of n favoured (determined solely by phase space) increases dramatically as the mass of the parent particle increases for fixed " size " d. For the ψ, the favoured value is $n \simeq 4$ for $d = 1$ fm and is $n \simeq$ 7–8 for $d = m_\pi^{-1}$. (ii) The observed p_T damping in hadron collisions and the $|p|$ damping in $e\bar{e}$ collisions, when extended to decays, also lead to the same conclusion. (iii) At the most elementary level, we may appeal to the uncertainty principle to say that if the initial position of a decay product is uncertain to an amount d, the " size " of the decaying particle, its momentum is likely to be of the order of $p \simeq \hbar/d$: for $d = 1$ fm, $p \sim 200$ MeV. These points, some of which have recently been invoked (Yamaguchi 1975) for the colour models, may not all be independent.

For specifically photonic decays, we have to add to these the phenomenon observed by Feynman *et al* (1971) in a quark model setting and revived recently (Close 1975) in the context of colour models. This is perhaps the most important inhibitor of radiative decays and concerns the electromagnetic form factors involved. If these form factors are indeed damped with increasing photon energy (exponentially in a non-relativistic quark picture), the branching ratio into γ + hadrons will be reduced to a great deal (the decays into massive or a large number of hadrons being cut down by phase space). In view of this, our first naive expectation in I that the total radiative width of ψ may be as large as 200 keV is no longer to be given weight—we had taken then, with due caution, all form factors to be of order 1.

3.2. ψ *decay: details*

The decays of ψ into hadrons through its S_-^0-component [making up $\Gamma_h'(\psi)$] can occur only through an intermediate state containing an ("anomalous") photon and will satisfy $\Delta I = 0$ at one vertex and $|\Delta I| = 0, 1$ at the other. The final states will therefore have both $G = -$ and $G = +$ with equal *a priori* probability. [S_-^0 has $G = -$ in the model and S_+^0, $G = +$ though, of course, S and $\bar{S}$ are not eigenstates of G]. On the other hand, the ψ-decays proceeding through its P-component [and making up $\Gamma_h''(\psi)$] will lead to final states with the same quantum numbers as P itself, in particular $G = -$ since P has $G = -$. Let us define, for any hadronic final state or set of final states f,

$$R(f) = \sigma(e\bar{e} \to f)/\sigma(e\bar{e} \to \mu\bar{\mu}), \quad \text{off resonance,}$$

$$R_\psi(f) = \Gamma(\psi \to f)/\Gamma(\psi \to \mu\bar{\mu}), \quad r_\psi(f) = R_\psi(f)/R(f).$$

Then we expect, assuming the dominant contribution to S_-^0 decay to arise from the one photon intermediate state, $r_\psi(G = +)$ to be $\simeq 1$ but $r_\psi(G = -)$ to be significantly above 1. These expectations are well fulfilled experimentally (Lüth 1975): *e.g.*, r_ψ (even no. of pions) $\simeq 1$ while r_ψ (odd no. pions) $\gtrsim 6$; the value of $R_\psi(p\bar{p})$ is pronouncedly greater than the value of $R(p\bar{p})$ ($p\bar{p}$ in $I = 0$ has $G = -$).

In general therefore

$$\Gamma_h'(\psi) \simeq 2\Gamma(\psi \to G = +) \ll \Gamma_h''(\psi) \simeq \Gamma(\psi \to G = -)$$
$$- \Gamma(\psi \to G = +) \simeq \Gamma(\psi \to G = -).$$

We can thus use the value of G as a signature to separate the S_-^0 and P components of ψ in the decay products. The importance of this elementary remark lies in the fact that $G = -$ final states will have all quantum numbers same as the P.

Having seen that $\Gamma_h''(\psi)$ is larger than $\Gamma_h'(\psi)$, the question to be asked is whether this feature is understandable as arising from electromagnetic mixing. Since it is virtually impossible, starting from the mixing assumption, to calculate the value of r_ψ $(G = -)$ or $\Gamma_h''(\psi)$ in any credible way, we shall take the experimental value of r_ψ $(G = -)$ and estimate the mixing angle λ. For r_ψ $(G = -) \simeq 6$, we have $\mathrm{Br}(\psi \to G = -) \simeq 6 \times 1.25 \times 7\% = 53\%$, where 1.25 is the value of $R(G = -)$ and 7% is the value of $\mathrm{Br}(\psi \to \mu\bar{\mu})$. This gives

$$\Gamma_h''(\psi)/\Gamma(\psi) \simeq 44\%$$

and, using the observed widths of ψ and P (4.2),

$$\lambda \simeq 10^{-2},$$

entirely consistent with its electromagnetic origin.

Given the experimental facts that we have already used, our picture for the hadronic decays of ψ is then: $\mathrm{Br}(\psi \to G = -) \simeq 53\%$, of which $\sim 44\%$ come from the P-admixture and $\sim 9\%$ from the 1 photon annihilation of $e\bar{e}$ through the ψ; $\mathrm{Br}(\psi \to G = +) \simeq 9\%$ all from 1 photon decay; so that $\mathrm{Br}(\psi \to \text{hadrons}) \simeq 62\%$. Taking out the 14% of leptonic decays, it leaves approximately 24% still to be accounted for.

Within the paracharge scheme, all these remaining decays are radiative, being reduced (from their otherwise expected large probabilities) to this rather small number through the suppression mechanisms discussed in section 3.1. This suggestion is consistent with the very little that is already known about radiative ψ decays, namely (Wiik 1975) $\mathrm{Br}(\psi \to \eta'\gamma) \simeq 1.5\%$ (preliminary), $\mathrm{Br}(\psi \to \eta\gamma)$ being smaller, conforming to the expected rarity of decays into light 2-body states. Remembering that $\mathrm{Br}(\psi \to \rho\pi)$ is also only $\sim 1.5\%$, out of a total $\mathrm{Br}(\psi \to G = -)$ of $\sim 50\%$, we can confidently take this number as an indication of $\mathrm{Br}(\psi \to \text{hadrons} + \gamma)$ being at least as large as the expected 25%. Within the paracharge scheme, the only other comparable radiative mode is into $f' + \gamma$. And among the more-than-2-body radiative modes, which are probably more important ones, quark conservation implies the dominance of states either having K and $\bar{K}$, or having one hidden strangeness particle.

We have yet to discuss SU_3 selection rules in ψ-hadronic decays. Because of the dominance of $G = -$ states, as we have seen, what is relevant for this question is the SU_3 nature of the *non-χ wave function* of P since, according to us, it is this small deviation from ideal mixing which is responsible for the P-width, the paracharge threshold being $\simeq 2m[S(PS)] \simeq 5.6$ GeV $> m(P) \simeq 4.1$ GeV. In general, the P-wave function, including the impurity, has the form

$$|P\rangle = (1 + |a|^2 + |a'|^2)^{-1/2} [|\bar{\chi}\chi\rangle + a|\bar{\lambda}\lambda\rangle$$
$$+ (a'/\sqrt{2})(|\bar{p}p\rangle + |\bar{n}n\rangle)],$$

with $|a|, |a'| \ll 1$. The fact that the observed ψ-decay rates into hadrons appear to satisfy the relations valid for the decay of an SU_3-singlet (as in the near equality of $\mathrm{Br}(\psi \to \bar{p}p)$ and $\mathrm{Br}(\psi \to \bar{\Lambda}\Lambda)$) only means that $a \simeq a'/\sqrt{2}$. Given this, the "large" value $\mathrm{Br}(\psi \to \phi\pi^+\pi^-)/\mathrm{Br}(\psi \to \omega\pi^+\pi^-) \simeq 0.2$ is not surprising; in fact what is to be explained then is the deviation of this ratio from 1. Phase space and, even more importantly, the fact that there is an extra process which contributes to the ω channel but not to the ϕ channel (figure 1) are responsible for this. Notice that we use the quark continuity rule here only in its weakest Okubo form (no "hairpin" graphs)'

We conclude our discussion of ψ decays by repeating that, in the light of the considerations of section 3.1, all aspects of ψ decays are in accord with the paracharge scheme, to the (semiquantiative) extent to which calculations are possible. The outstanding feature of these decays is that even though they are of electromagnetic origin, the hadronic decay rates (order α^2) are larger than the radiative rates (order α). Any mystification this may have caused disappears if we compare this situation with the case of η decays (Close 1975). All the decays of η are also electromagnetic and so its mixing with π^0 is important. In our view it is the π^0 component in the η which is responsible for making $\mathrm{Br}(\eta \to 3\pi)$ as large as 54% while $\mathrm{Br}(\eta \to 2\pi\gamma)$ is only 5%. The other dominant η mode, into 2γ, is of course forbidden to the ψ. To take another example* which is even closer to the ψ situation, one might naively expect $\mathrm{Br}(\omega \to \pi^+\pi^-)$ to be about two orders of magnitude smaller than $\mathrm{Br}(\omega \to \phi^0\gamma)$. Experimentally they are not very different, 1.3% and 9% respectively. Here again we believe that the radiative mode is somewhat suppressed by the form factor and the 2π mode enhanced by the large width of ρ.

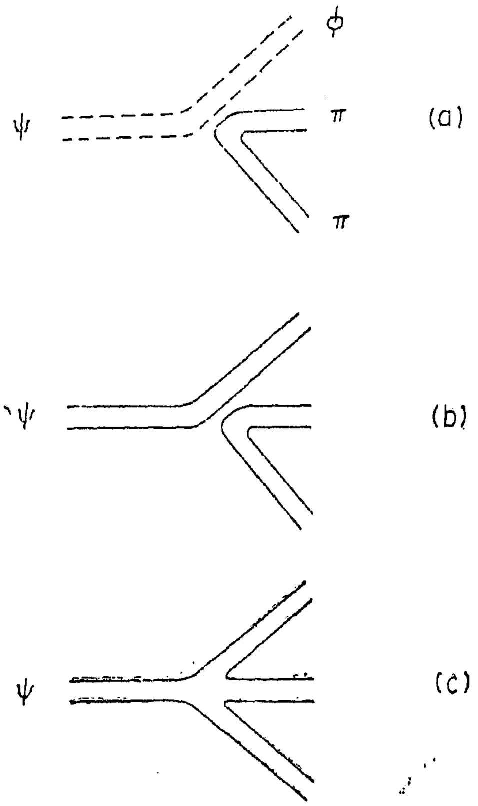

Figure 1. Quark diagrams describing the decay of ψ (via its p admixture) into (*a*) $\phi\pi\pi$, (*b*) and (*c*) $\omega\pi\pi$. Full lines are p or n quarks and the dashed lines are λ quarks. In (*b*) and (*c*), each of the final state particles can be the ω or a π.

* We are grateful to H S Mani for drawing our attention to this example.

3.3. ψ' decay detail

The experimental information here is much less detailed. The firmest numbers available are for the strong channels $\psi' \to \psi +$ hadrons. They are in general agreement with the qualitative conclusions of 1: $\psi' \to \psi + 2\pi$ with 2π in $I = 0$ *is* the dominant mode. The only other number known (Lüth 1975) is Br $(\psi' \to \psi\eta)$ $\simeq 4 \pm 2\%$. Its smallness is due to the fact that it is SU_4-forbidden, as disucssed in I.

All ψ' decays into ordinary (paraneutral, $Z = 0$) hadrons are again of electromagnetic origin and therefore the considerations of section 3.1 are the determining factors in their description. In the absence of better knowledge, we shall make do with the same mixing angle, *i.e.*, $\lambda' \simeq \lambda \simeq 10^{-2}$, for this purpose. Since Br $(\psi' \to \mu\bar{\mu})$ is only 1%, Br $(\psi' \to \gamma \to$ hadrons) is small, $\simeq 3\%$, so that Br $(\psi' \to Z = 0, G = +) \simeq 1.5\%$. With a mixing angle the same as in ψ-decays, we have then Br $(\psi' \to Z = 0,\ G = -) \simeq 10\%$. This kind of estimation can in fact be made for any exclusive $G = -$ channel (knowing the corresponding quantity for ψ) and gives, for example,

$$\mathrm{Br}\,(\psi' \to 2\pi^+ 2\pi^- \pi^\circ) \simeq 0{\cdot}5\%$$

$$\mathrm{Br}\,(\psi' \to p\bar{p}) \simeq 0{\cdot}03\%.$$

These are the only two measured branching ratios for hadronic decays not involving the ψ (3.1) and the experimental values (Abrams 1975) are $0.35 \pm 0.15\%$ and $0.04 \pm 0.02\%$ respectively. The important point is that when the decays are electromagnetic, all hadronic branching ratios of ψ' are indirectly determined by the branching ratio into $\mu\bar{\mu}$ through the intermediary of the value of R and the mixing angle. The numbers written above depend on the value of the mixing angle, $\lambda \simeq 10^{-2}$, but they are not so important as the qualitative fact that all ψ' decays into paraneutral hadrons are suppressed to the extent of the relative smallness of its width into $\mu\bar{\mu}$ (Das *et al* 1975 *d*)†. *Thus the apparent violation of G in ψ' decays vis-a-vis its apparent conservation in ψ-decays is not a mystery in the paracharge scheme.*

The broad conclusion of the last paragraph is that Br $(\psi' \to Z = 0) \simeq 12\%$. From this and the experimental values Br $(\psi' \to |Z| = 1) \simeq 52\%$ (mostly $\psi 2\pi$) and Br $(\psi' - l\bar{l}) \simeq 2\%$, we are left with an unaccounted 35%; we suggest again that most of this describes photonic decay. A substantial share of this will have many ($Z = 0$) hadrons, always including η, η', f' or a $K\bar{K}$ pair, in the final state. A small fraction of two body decays should be seen, with $\eta'\gamma$ and $f'\gamma$ dominating. There are also channels open to ψ' which are closed to ψ: $\chi\,(3.5)\,\gamma$, $\chi\,(3.4)\,\gamma$, $\chi\,(3.3)\,\gamma$ and $S_+^0\,(3.1)\,\gamma$ (S_+^0 is the $C = +$ partner of ψ (3.1)) where $\chi\,(3.5) \equiv S^0\,(PS)$, $\chi\,(3.4) \equiv S_+^\circ\,(T)$ and $\chi\,(3.3) \equiv S_+^\circ\,(A)$. $\chi\,(3.4)$ and $\chi\,(3.3)$ were identified through these, and the rates were found to be, not surprisingly, small.

† In a recent paper, Okubo (1976) has written down a phenomenological form for the effective Hamiltonians governing ψ and ψ' decays into ordinary hadrons that ensures these features of ψ'-decays. These formes essentially lead to the same ψ and ψ' decay amplitudes as in the paracharge model with mixing taken into account. For the first statement of this result see Das *et al* (1975*d*). In fact the choice $\lambda'/\lambda \simeq 1/\sqrt{2}$ leads to Okubo's results.

We have not attempted to understand the leptonic decay rate here, especially why it is small for ψ' decays, because we do not know any reliable way of doing so. Not being convinced of the soundness of using simple, non-relativistic, weak potential dynamics in this context (as we have seen, for much of the new hadron spectroscopy, simple and well-tried ideas of symmetry and symmetry breaking suffice) we are unable to duplicate the methods extensively used in charmonium models for this purpose. The other popular method of relating leptonic widths is that of using spectral function sum rules. Here, there is no good reason to limit the saturating states to only one multiplet. When all vector meson intermediate states are put in, the sum rules have little predictive power.

4. Other properties of the currents

The presence of the $|\triangle Z| = 1$ Pauli-type electromagnetic current which transforms as $3 \oplus 3^*$ under SU_3 is difficult to detect in the interactions of ordinary hadrons since they belong to representations with triality zero. In particular, it makes no contribution to baryon magnetic moments. It will contribute to virtual photonic matrix elements, *e.g.*, electromagnetic mass *shifts*. The extra effective Hamiltonian will have two parts with triality zero, tranforming as a singlet and an octet. Thus the Coleman-Glashow sum rule for the 8-baryon mass *differences* will be unaffected.

The $\triangle Z = 0$ members of $\mathcal{G}_\mu$, if they occur, belong to an octet and to singlets. As above, the octet will not lead to any deviations from the conventional SU_3 sum rule predictions. The effect of the singlet is as yet hard to pinpoint (Gupta and Kogerler 1975).

The most important general consequence of the current $\mathcal{G}_\mu$ is in highly inelastic *e-p* and μ-*p* scattering and in $e\bar{e}$ annihilation into hadrons. Deviations from Bjorken scaling and the constancy of R will begin to appear once the paracharge threshold is crossed. And if arguments based on the dimensionality of the Pauli interaction term remain valid at all energies (*i.e.*, if entirely new and unsuspected phenomena do not take over at higher energies) then, *asymptotically*, Bjorken scaling will be violated strongly and R will increase linearly. Evidence for scaling violation in μ-Fe inelastic scattering has recently been reported (Chang *et al* 1975; Watanabe *et al* 1975). As for the behaviour of R, the present values of s are still too close to the resonances, actually seen and those expected in the paracharge model, to permit us to use 'asymptotic' considertions and so to enable us to say anything very definite. There is also the possibility that the form $\bar{\psi}\sigma_{\mu\nu}\,\psi\, F^{\mu\nu}$ of the " anomalous " current coupling is an " intermediate' energy manifestation of a more fundamental and more conventional electromagnetic interaction of the quarks valid perhaps at extremely high energies (a comparison with the role of the anomalous magnetic moments of the nucleons in low energy electromagnetic processes in light nuclei is pertinent here). In that case we cannot make any categorical statement about truly asymptotic scaling. At any rate, what is certainly true is that neither the unexpectedly large value of R nor the (less spectacular) deviation from Bjorken scaling in inelastic muon scattering is an embarrassment to our picture.

We would also like to mention here that the paracharge scheme incorporates in a natural way a gauge theory of weak interactions (unified, if desired, with the "normal" electromagnetic interactions). The basic idea is that muon-number and paracharge play parallel roles in describing leptons and quarks so that muon-number is not absolutely conserved. The theory deals with V–A currents and has *no* room for anomalous weak currents, but fits in well with anomalous electromagnetic currents. Several variants of the basic structure are possible. One version which accounts satisfactorily for the standard weak interactions, including the existence and properties of the neutral currents has already been published (Das *et al* 1975 *c*). Extensions to include the newer phenomena alluded to in the introduction are under consideration.

5. Conclusions

The paracharge scheme seeks for the present to be only a phenomenological one. Our aim has been to extend in the most economical way the standard SU_3 symmetry description and classification of ordinary hadrons to incorporate the newly discovered particles and their unusual properties. The introduction of chargeless Pauli currents (Z-violating currents whose charges do not vanish are not consistent with the charge superselection rule, see I) is admittedly unconventional. But it is nowhere in contradiction with any previously known hadronic phenomena and at the same time provides a very satisfactory description of the new hadrons, as we have tried to show in this paper. We have of course not attempted any fundamental understanding of such currents. They are, for example, at least superficially unrenormalizable. We feel that such attempts, being difficult and deep, are best postponed to a later time when (and if) the picture we propose proves its phenomenological worth unambiguously. Since the shape of a future fundamental theory of hadrons (and quarks) is far from clear yet, we feel that keeping to a phenomenological point of view may prove safer.

A number of tests of the model have been proposed in the main part of the paper. The outstanding one is the existence and properties of the D-mesons which will complete the vector ψ-multiplet. Their masses are around 3 GeV. The most promising way of looking for them is in the decays $\psi' \to D + \bar{K}, \bar{D} + K$; the branching ratios will be small, of the same order as $\mathrm{Br}(\psi' \to \psi\eta) \simeq 4\%$. If radiative modes are suppressed for the reasons discussed earlier, their decays into hadrons will not be negligible; in any case the final hadrons will have $|Y| = 1$, and so K-mesons are always present. The total widths will be rather less than that of ψ (no mixing) and a good signature therfore will be a small and narrow spike in the momentum distribution of K-mesons coming from ψ' decays.

A second and equally conclusive test will be the detection of *odd* charge conjugation "intermediate" states, degenerate with their even charge conjugation partners in a careful search of the missing mass spectrum in $\psi' \to \pi^+\pi^- +$ anything.

We also mention a third check, specifically sensitive to the role of the chargeless current, $\mathfrak{g}_\mu$. In decays such as $\psi \to$ hadrons $(\geqslant 2) + \gamma$, the matrix element should vanish as the momentum of the photon goes to zero. Its consequences can be looked for in the energy spectrum of the final state hadrons.

Since in our scheme in any given meson multiplet, the S states (and the nearly degenerate D states) have the lowest mass, our picture differs significantly from the charm models in having no undiscovered, lower lying new hadrons. At the same time (in contrast with colour models) it remains economical in the introduction of new hadrons.

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