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Gauge Model for the Electromagnetic Form Factor and the ρ′ Meson

Kazuo Fujikawa* and P. J. O'Donnell†

Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Silver Street, Cambridge, CB3 9EW, England

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Following the basic idea of the spontaneously broken gauge theory and ρ dominance and its universality, we propose a simple model for the ρ′ meson. With the identification of the Higgs scalar meson with the ε meson, we are able to give a satisfactory description of various results in electron colliding-beam experiments. The suppression of the 2π decay mode of the ρ' meson relative to the 4π mode is determined by the scale dimension of the interaction terms. The pion form factor and the Dirac isovector form factor of the nucleon are identical in the present model, and they are in agreement with experiment.

The idea of vector-meson dominance of electromagnetic currents and vector-meson universality has played an important role in the development of hadron physics.[1] Recent developments of the gauge theory[2-4] indicate that the theory for massive vector mesons can be formulated in a self-consistent manner. The renormalizability of the spontaneously broken gauge theory, in particular, suggests that the tree diagrams based on such a theory may be rather stable against perturbation due to higher-order effects. The salient feature of the gauge theory based on the Higgs-Kibble mechanism[2] is the existence of extra scalar mesons, which we call the Higgs scalars in the following. A study[5] of the high-energy behavior of the vector-meson scattering amplitude based on the tree diagrams shows that an effective Lagrangian which satisfies the unitarity bound may always contain such scalar mesons. The zero-slope limit of the dual-resonance[6] model, which corresponds to the spontaneously broken gauge theory, also indicates such mesons. In particular the mass of the Higgs scalar is degenerate with that of the vector-meson multiplets in the zero-slope limit of the dual theory.

On the other hand, recent experiments[7] in the electron storage ring strongly indicate the existence[8] of the heavier isovector meson ρ' at $m_{\rho'} \simeq 1.6$ GeV. The decay mode of the ρ', if treated as a real resonance, shows an interesting pattern. It decays predominantly into $\rho\epsilon$ states with other decay modes such as 2π and π"A_1" appearing to be strongly suppressed.[8]

In the present note we show that the spontaneously broken gauge theory based on the field-mixing-type coupling[9-11] (or current-field identity) can give an interesting model for the ρ' meson. In particular the identification of the Higgs scalar meson with the ϵ meson in the spirit of the zero-slope limit of the dual-resonance model gives a satisfactory *quantitative* description of various properties of the ρ' meson. Our approach is in its spirit close to that of Gell-Mann, Sharp, and Wagner[12] to ordinary vector-meson dominance. We take the gauge theory as a guiding principle and formulate the model in a semidispersive manner. Although it is possible to write a class of Lagrangians which satisfy our requirements, we abstract only the most common and fundamental aspects of the gauge theory. In view of the well-known complications on strong interactions, this approach seems to be reasonable. Our results in fact indicate that such basic properties abstracted from the gauge theory provide a simple unified picture of various phenomena at low energies in which the hadron isovector electromagnetic current is involved. In particular our model combined with ρ universality suggests that the pion form factor and the isovector Dirac form factor of the nucleon are identical and they are given by a simple universal function. This form factor seems to be in agreement with the observed electromagnetic form factors for $-q^2 \lesssim m_{\rho'}^2$.

The basic physical picture of our model is shown in Fig. 1 (to lowest order in e the photon couples charged particles only through ρ' and ρ). The major motivation for taking this picture is that it does the least harm to well-established properties such as ρ dominance and its universality. From the gauge-theory point of view it is also the easiest way to incorporate the extra vector meson ρ' into the theory where the ρ meson is already included (e.g., the ordinary SU(2)×SU(2) gauge model).[13]

The various coupling constants of the diagrams in Fig. 1 are determined as follows. We first discuss the coupling between ρ' and other hadronic mesons. For this purpose we look at the mass term of the ρ-meson triplet in the Lagrangian (the spontaneously broken gauge theory is a theory on how to generate various masses)

$$\tfrac{1}{2} m_\rho^2 \vec{V}_\mu \vec{V}^\mu , \qquad (1)$$

where $\vec{V}_\mu$ denotes the ρ-meson field. The field-

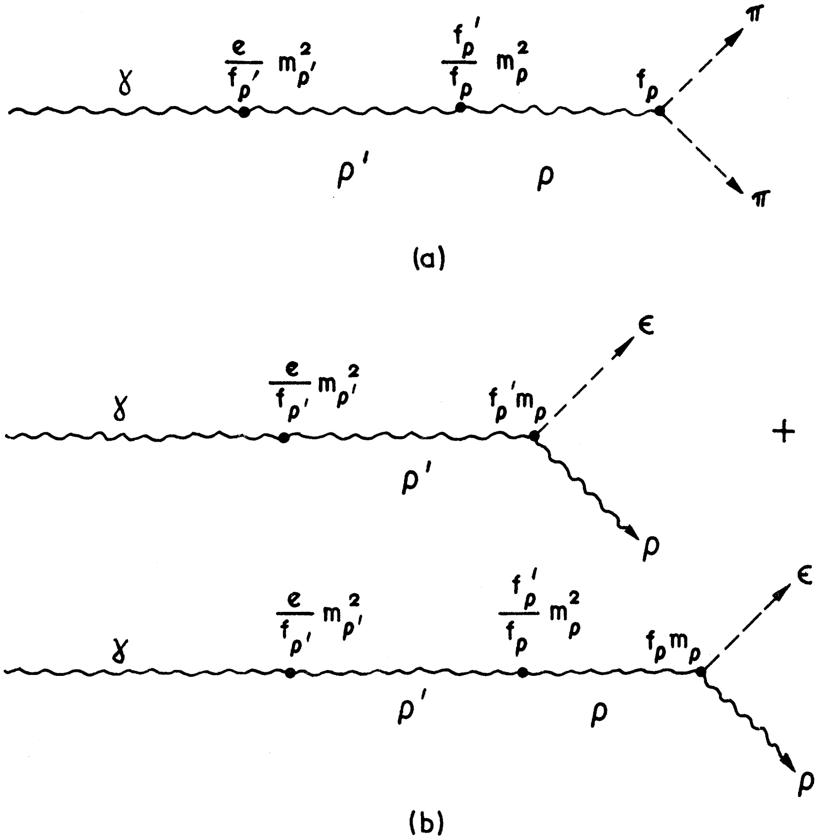

FIG. 1. Coupling schemes in our model.

mixing-type coupling indicates the following minimal insertion[9] in Eq. (1):

$$\vec{V}_\mu \to \vec{V}_\mu - (f_{\rho'}/f_\rho)\vec{B}_\mu\,, \tag{2}$$

where $\vec{B}_\mu$ is the ρ' field, and f_ρ and $f_{\rho'}$ correspond to the Yang-Mills gauge coupling constant for ρ and ρ' mesons, respectively. The spontaneously broken gauge theory also indicates another "minimal" insertion

$$m_\rho \to m_\rho + \tfrac{1}{2} f_\rho\,\phi(x)\,, \tag{3}$$

where $\phi(x)$ is the Higgs scalar field which we identify with the ϵ field in the following. Equation (3) is valid for the isospin symmetry [i.e., SU(2)]. If one works on the Abelian group,[11] for example, Eq. (3) becomes $m_\rho \to m_\rho + f_\rho\,\phi(x)$. Note that we are working in the unitary gauge[4] and $\langle \phi \rangle_{\rm vac} = 0$. Equation (1) is thus replaced by

$$\tfrac{1}{2}[m_\rho + \tfrac{1}{2} f_\rho\,\phi(x)]^2[\vec{V}_\mu - (f_{\rho'}/f_\rho)\vec{B}_\mu]^2 = \tfrac{1}{2} m_\rho^2 \vec{V}_\mu \vec{V}^\mu + \tfrac{1}{2} m_{\rho'}^2 (f_{\rho'}/f_\rho)^2 \vec{B}_\mu \vec{B}^\mu - (f_{\rho'}/f_\rho) m_\rho^2 \vec{V}_\mu \vec{B}^\mu$$
$$- f_{\rho'} m_\rho\,\phi(x) \vec{V}_\mu \vec{B}^\mu - \tfrac{1}{4} f_\rho f_{\rho'}\,\phi^2(x)\,\vec{V}_\mu \vec{B}^\mu + \tfrac{1}{2} f_\rho m_\rho\,\phi(x)\,\vec{V}_\mu \vec{V}^\mu + \text{other terms.} \tag{4}$$

The third term in Eq. (4) gives the coupling constant in Fig. 1(a) and the fourth and sixth terms determine the coupling constant in Fig. 1(b). The fifth term contributes to the decay of the ρ' meson via virtual states; the determination of such contributions is more model-dependent but it may count for rather high-multiplicity events measured at the ρ' mass region (see also following discussions). The sixth term contributes to the process $\gamma + \gamma \to \epsilon$ in the colliding-beam experiment. The second term gives rise to a part of the mass of the ρ' meson. In the following we assume that

$$f_{\rho'} \lesssim f_\rho\,. \tag{5}$$

Thus the $\phi(x)$ field gives only a small portion of the ρ' meson mass. Under this assumption the diagonalization of the mass matrix leads to a minor redefinition of various parameters in Eq. (4). We can therefore take the coupling constants in Fig. 1 as the physical (renormalized) coupling constants. The coupling scheme given in Eq. (4) is correct for an SU(2) model such as the zero-slope limit of the dual model discussed by Gervais and Neveu.[6] When one goes to a chiral SU(2)×SU(2) model such as the one discussed by Bardakci,[10] the mass part becomes slightly more complicated. But the form given in Eq. (4) still gives a correct coupling scheme for the processes we are interested in. (In this respect we note that the parity partner of the Higgs scalar meson in Bardakci's model,[10] which was identified as η (or η') by Bardakci, *strongly* decays into 3π states. Therefore it can not be identified with any low-lying mesons.) The chiral SU(2)×SU(2) problem is discussed later. Incidentally the model by Bardakci is particularly interesting because $\phi(x)$ in his model corresponds to the dilaton; this may give another justification for identifying $\phi(x)$ with the ϵ meson.[11,14] The photon-ρ' coupling in Fig. 1 is similarly determined by the following term in the ρ' mass part:

$$\tfrac{1}{2}[m_{\rho'} + \tfrac{1}{2} f_{\rho'} \phi'(x)]^2 [\vec{B}_\mu - (e/f_{\rho'})A_\mu]^2 = \tfrac{1}{2} m_{\rho'}^2 \vec{B}_\mu \vec{B}^\mu - (e/f_{\rho'}) m_{\rho'}^2 B_\mu^3 A^\mu + \text{other terms}, \tag{6}$$

where A_μ is the photon field, and ϕ' is another Higgs scalar meson which generates the mass for the ρ' meson. (In the spirit of the zero-slope limit of the dual model, we take the mass of this meson at least comparable with ρ' mass. Therefore this meson is not important in the following discussions.)

Figure 1(a) immediately gives the pion form factor

$$F_\pi(q^2) = \frac{m_\rho^2}{q^2 - m_\rho^2} \frac{m_{\rho'}^2}{q^2 - m_{\rho'}^2} . \tag{7}$$

This is shown in Fig. 2 where the ordinary ρ-dominant form is also shown for comparison. Equation (7) is consistent with experiment[15] although the well-known theoretical ambiguity involved in extracting the pion pole term in the electroproduction data prohibits any definite statement. Equation (7) can also be written as

$$\left[\frac{1}{f_\rho} \frac{m_{\rho'}^2}{(q^2 - m_{\rho'}^2)}\right] \frac{m_\rho^2}{q^2 - m_\rho^2} f_\rho . \tag{7'}$$

This shows that the effective coupling constants $f_{\rho\pi\pi}$ and $f_{\rho\gamma}$ measured at $q^2 = m_\rho^2$ are related by

$$\frac{f_{\rho\pi\pi}^2}{4\pi} : \frac{f_{\rho\gamma}^2}{4\pi} = \frac{f_\rho^2}{4\pi} : \left(\frac{f_\rho^2}{4\pi}\right)\left(\frac{m_{\rho'}^2 - m_\rho^2}{m_{\rho'}^2}\right)^2 \simeq 3:2 . \tag{8}$$

One can also confirm this by first diagonalizing the mass matrix. This result can be compared with the experimental result[16]

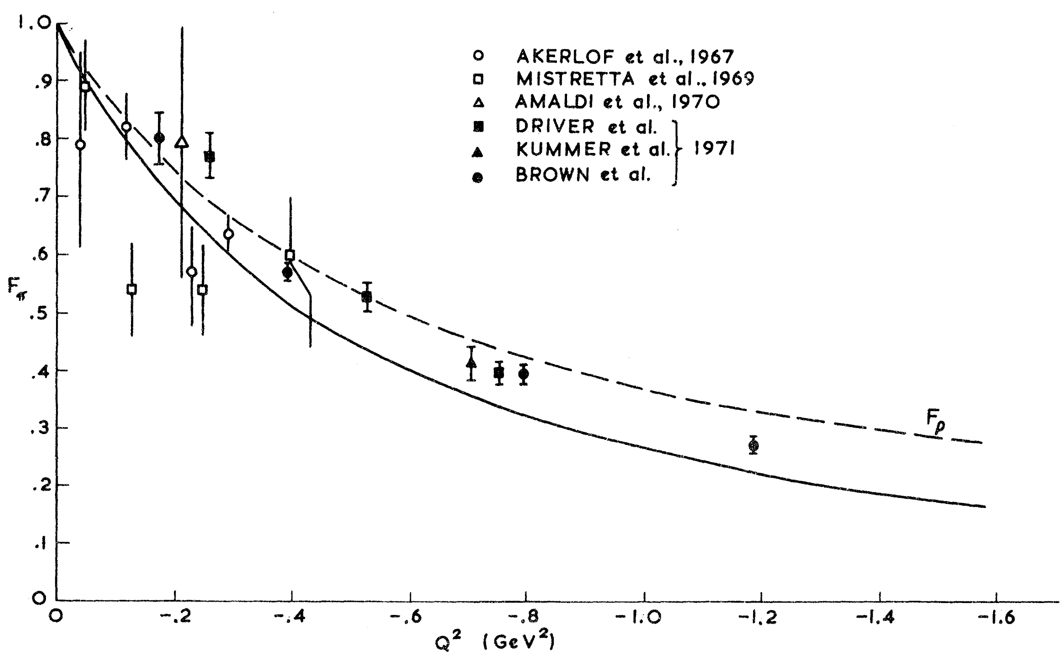

FIG. 2. Pion form factor. The full line shows the form factor in our model; the dashed line gives the ρ dominance form factor for comparison. The data are from the review by Berkelman (Ref. 15). Here $m_{\rho'} = 1.6$ GeV; if one takes $m_{\rho'} = 1.7$ GeV agreement with the data is further improved (see Fig. 3 and also Ref. 18).

$$\frac{f_{\rho\pi\pi}^2}{4\pi}:\frac{f_{\rho\gamma}^2}{4\pi}=(2.84\pm0.43):(2.26\pm0.25) \tag{9}$$

in the narrow-resonance interpretation. The unitarity correction in the more sophisticated treatment[17] is approximated by a single-pole contribution at $q^2=m_{\rho'}^2$ in the present model. The ρ-meson universality based on the Yang-Mills couplings also indicates

$$F_{1V}(q^2)\equiv F_\pi(q^2), \tag{10}$$

where F_{1V} is the isovector part of the nucleon Dirac form factor. Equation (10) combined with the following relation:

$$\frac{G_M^p(q^2)}{\mu_p}=\frac{(1-\tau)F_{1V}(q^2)}{(1-\mu_V\tau)}, \quad \tau=\frac{q^2}{4M^2}, \tag{11}$$

has been discussed previously, and it gives a satisfactory description of $G_m(q^2)$ for small q^2 values, $-q^2\lesssim m_{\rho'}^2$.[18] In fact the existence of the ρ' meson with a mass of >1.6 GeV was first suggested based on Eq. (11).[18] For large q^2 values, Eq. (11) approaches a dipole form, but it is outside the scope of the present simple gauge model.

We next discuss ρ'-production experiments.[7,8] Figure 1(a) shows that the 2π decay mode in the present model proceeds via a ρ-meson pole ($\rho^+\rho^-$ and π"A_1" decay modes also proceed in a similar way and they are suppressed relative to the $\epsilon\rho$ mode). The partial decay widths for $\rho'\to2\pi$ and $\rho'\to\epsilon\rho$ are given by (see Fig. 1)

$$\Gamma(\rho'\to2\pi)=\frac{f_{\rho'}^2}{4\pi}\frac{m_\rho^4(m_{\rho'}^2-4\mu^2)^{3/2}}{12m_{\rho'}^2(m_{\rho'}^2-m_\rho^2)^2}, \tag{12}$$

$$\Gamma(\rho'\to\rho\epsilon)=\frac{f_{\rho'}^2}{4\pi}\frac{m_\rho^2}{6m_{\rho'}}\left(1-\frac{(m_\rho-m_\epsilon)^2}{m_{\rho'}^2}\right)^{1/2}\left(1-\frac{(m_\rho+m_\epsilon)^2}{m_{\rho'}^2}\right)^{1/2}\left(1+\frac{(m_{\rho'}^2+m_\rho^2-m_\epsilon^2)^2}{8m_\rho^2m_{\rho'}^2}\right)\left(\frac{1}{1-m_\rho^2/m_{\rho'}^2}\right)^2. \tag{13}$$

The decay ratio is therefore given by

$$\frac{\Gamma(\rho'\to2\pi)}{\Gamma(\rho'\to\rho\epsilon)}\simeq\frac{1}{7.5}. \tag{14}$$

Namely the 2π mode amounts to only $\approx15\%$ of the $\rho\epsilon$ mode. This is in line with experiment.[8] We next calculate the total production cross section for $e^++e^-\to\pi^+\pi^-\pi^+\pi^-$. Figure 1(b) gives

$$\sigma=\tfrac{2}{3}\sigma(e^+e^-\to\rho\epsilon)$$
$$=\frac{4\pi\alpha^2}{9}\frac{m_\rho^2}{(q^2)^2}\left(1-\frac{(m_\rho-m_\epsilon)^2}{q^2}\right)^{1/2}\left(1-\frac{(m_\rho+m_\epsilon)^2}{q^2}\right)^{1/2}$$
$$\times\left(1+\frac{(q^2+m_\rho^2-m_\epsilon^2)^2}{8q^2m_\rho^2}\right)\frac{(m_{\rho'}^2)^2}{((q^2-m_{\rho'}^2)^2+m_{\rho'}^2\Gamma^2)}\frac{1}{(1-m_\rho^2/q^2)^2}. \tag{15}$$

Equation (15) is plotted in Fig. 3 where the *total* decay width of the ρ' meson Γ is taken to be 500 MeV. Unfortunately the cross section is fairly sensitive to the total decay width Γ. It is, however, still interesting that the simple gauge model determines the various coupling strength more or less correctly. Due to the photon propagator the peak is shifted to the low-energy side relative to the Breit-Wigner resonance shape. We also note that the tail in the lower end of the spectrum may be explained as $\rho'\to\pi$"A_1" events. The angular distribution of the ρ° meson in the center-of-mass frame of the ρ' meson is given by

$$\frac{d\sigma}{d\cos\theta}\Big/\sigma\bigg|_{q^2=m_{\rho'}^2}=\frac{1}{2}\frac{1-\eta\cos^2\theta}{1-\frac{1}{3}\eta}, \tag{16}$$

where $\cos\theta$ is the angle between the colliding electron and the outgoing ρ meson. The parameter η is given by

$$\eta=-\frac{1-\dfrac{(m_{\rho'}^2+m_\rho^2-m_\epsilon^2)^2}{4m_{\rho'}^2m_\epsilon^2}}{1+\dfrac{(m_{\rho'}^2+m_\rho^2-m_\epsilon^2)^2}{4m_{\rho'}^2m_\epsilon^2}}\simeq0.13. \tag{17}$$

This shows that the angular distribution of the ρ meson is almost uniform in the rest frame of the ρ' meson. Before we proceed further we would like to comment on the decay width given by Eqs. (12) and (13). If one assumes a sort of universality,

$$f_{\rho'/4\pi}^2\simeq f_\rho^2/4\pi\simeq3, \tag{18}$$

we have from Eqs. (12) and (13),

$$\Gamma(\rho'\to\rho\epsilon)+\Gamma(\rho'\to2\pi)\simeq280\text{ MeV}. \tag{19}$$

In view of Fig. 3, this value seems to be rather small compared with the total decay width Γ. This

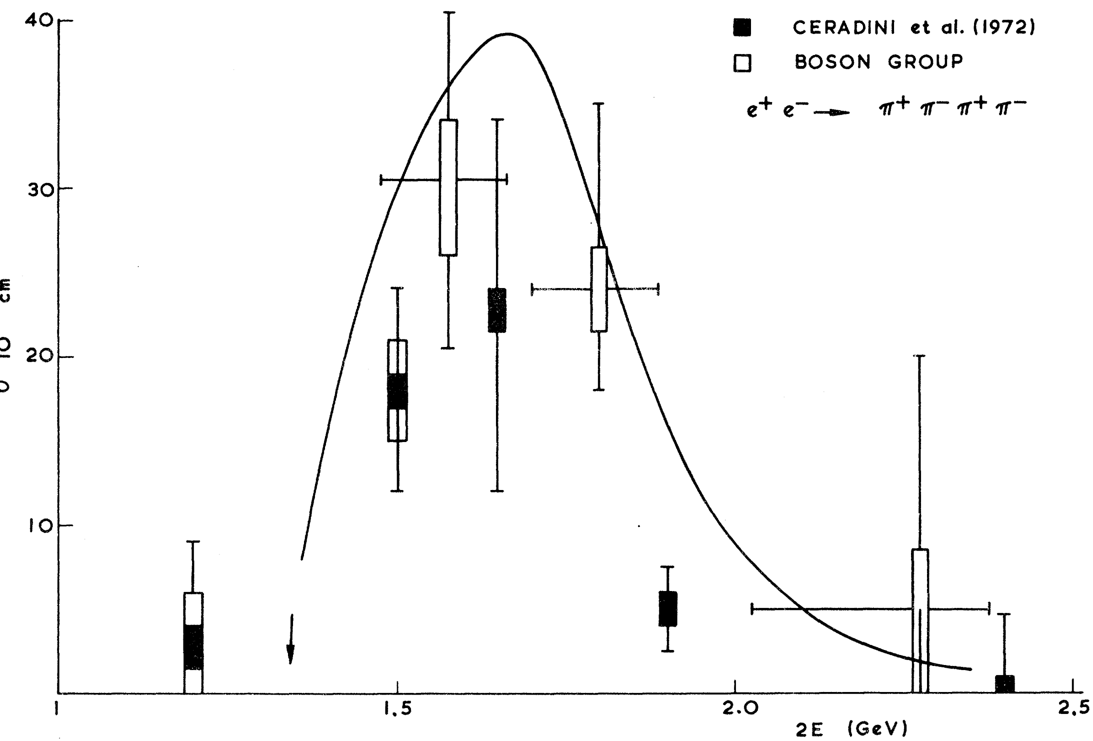

FIG. 3. Cross section for charged 4π production processes. The data are from the review by Diebold (Ref. 8). The curve corresponds to $m_{\rho'}=1.7$ GeV and $\Gamma=0.5$ GeV. Arrow indicates the threshold for $\epsilon\rho$ production.

indicates that either $f_{\rho'}$ is slightly larger than f_ρ or the ρ' decays into other multiparticle channels. In fact experiment (see Bacci *et al.*[7]) indicates that there are substantial multiparticle ($n>4$) events in the energy region of the ρ' meson (even comparable with 4π events). It is therefore not entirely unreasonable to assume that some part of the ρ', say 30–40%, decays into such multiparticle channels. In this case we can maintain the interesting universality relation (18). From the gauge theory point of view it is also desirable [see Eq. (5)]. In any case, in the present physical picture, the photon goes entirely via ρ' into other hadron states. Therefore Eq. (19), the total width $\Gamma\simeq 500$ MeV, and the *measured* multiparticle ($n>4$) events are in fact consistent with each other.

Figure 1(a) also explains why the ρ' photoproduction is suppressed relative to the ρ production.[8] This is seen by rewriting Eq. (7) as

$$F_{1V}(q^2)=F_\pi(q^2)$$
$$=\frac{1}{m_{\rho'}^2-m_\rho^2}\left[\frac{m_\rho^2 m_{\rho'}^2}{q^2-m_\rho^2}-\frac{m_\rho^2 m_{\rho'}^2}{q^2-m_{\rho'}^2}\right]. \quad (20)$$

For $q^2=0$, the coupling strength to the source current of the ρ' relative to the ρ is $m_\rho^2/m_{\rho'}^2$. The real photon therefore consists mainly of the ρ meson. The production cross section of ρ' will pick up a suppression factor $(m_\rho^2/m_{\rho'}^2)^2\sim\frac{1}{20}$ compared with the ρ meson [the contribution from Fig. 1(b), which depends on detailed hadron dynamics, may modify this estimate].

Considering the rather simple theoretical input, the present model describes well the isovector hadron electromagnetic phenomena in the limited kinematical region. In particular it is interesting that our model directly connects the suppression of the 2π decay mode of ρ' with the pion and nucleon form factors. This model also makes it more understandable why enormously strong interference between ρ and ρ' as expressed by Eq. (20) and the precocious scaling in the deep-inelastic electroproduction process[19] can coexist. As was explained previously,[11,14] Fig. 1(b) contains higher scale dimension than Fig. 1(a). [The suppression of the 2π decay mode in Eq. (14) is also due to this scale dimension.] Therefore a diagram like Fig. 1(b) becomes more important for large negative q^2 ($|q^2|\approx m_{\rho'}^2$). Figure 1(b) is not affected by strong interference between ρ and ρ': It is therefore expected to have rather smooth behavior which is necessary to explain the early scaling in the SLAC experiment. This picture is also consistent with the basic idea of generalized vector-meson dominance,[20] namely, heavier mesons become more important for larger momentum transfers (or small distances ~ heavy mesons). Figure 1(b) also suggests that "ϵ fragmentation" of the virtual photon may be observed at SLAC. However, we note that the present picture does not quite solve the difficulty related to the small ratio $R=\sigma_s/\sigma_T$.[11] This may indicate that the ratio R is strongly dependent on the hadron dynamics as well as on the structure of the current.

We also note that it is in principle possible to insert additional heavier mesons between the photon and ρ' in Fig. 1. However, when we go to the q^2 region where such heavy mesons become important, the other end of the coupling scheme in Fig. 1 becomes very unstable (heavy mesons can quickly decay by emitting many scalar mesons). Therefore a simple field-theoretical model will not work in such cases.

Finally we would like to comment on the chiral SU(2)×SU(2) model. As is well known the ordinary chiral effective Lagrangian[13] (and also the model by Bardakci[10]) predicts a strong q^2 dependence of the coupling constant $f_{\rho\pi\pi}$ if one assumes that the mass difference between ρ and "A_1" is entirely generated by the vacuum value of the σ field. More specifically a naive expectation based on the chiral model is[13] (at $q^2 \sim m_\rho^2$)

$$f_{\rho\pi\pi}^2/4\pi : f_{\rho\gamma}^2/4\pi \simeq 2:3 \ . \tag{21}$$

This disagrees with experiment [see Eq. (9)]. Besides the obscure status of the "A_1" meson itself,[8] this may indicate that the vacuum value of the σ field generates only the small portion of the m_ρ and m_{A_1} difference. In this case the $\rho\pi$"A_1" coupling becomes small and the decay mode $\rho' \to \pi$"A_1" is strongly suppressed in agreement with experiment[8] at $q^2 \sim m_{\rho'}^2$.

In conclusion the present model indicates that experimental data on hadron electromagnetic currents in the small-q^2 region ($|q^2| < m_{\rho'}^2$) may be consistently understood based on various interesting theoretical ideas such as ρ universality, spontaneously broken gauge theory, dual-resonance model, and dilation invariance, and the dilaton.

Note added in proof. A similar approach to the ρ' meson was also attempted by I. Bars, M. B. Halpern, and K. Lane [Berkeley report, 1973 (unpublished)].

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