PHYSICAL REVIEW D VOLUME 15, NUMBER 7 1 APRIL 1977

Couplings of vector mesons to tensor mesons and the Pomeron*

Kashyap V. Vasavada

Department of Physics and Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720 and Department of Physics, Indiana-Purdue University, Indianapolis, Indiana 46205†

(Received 23 September 1976)

We saturate the matrix elements of the stress tensor between vector-meson states with f, f', and the Pomeron, assuming that the coupling constants go like $1/m_V{}^2$ (m_V = vector-meson mass) within the symmetry-group (SU_3, SU_4, etc.) multiplet apart from the Clebsch-Gordan coefficients. It is found that (i) nonet (mass)^2 formulas are obtained, (ii) vector-meson–nucleon total cross sections are determined, with a $1/m_V{}^2$ dependence, and (iii) tensor-vector-vector couplings are obtained. All of these are in agreement with the experiments.

I. INTRODUCTION

The idea of tensor-meson dominance of the energy-momentum tensor $\theta_{\mu\nu}$ has been explored for a number of years.[1] Recently, this concept has become even more attractive because of its possible connection with a gravitation-type theory of strongly interacting particles. In previous papers[2,3] we have attempted to build in the Pomeron (P) contribution along with that of f and f' mesons in $\theta_{\mu\nu}$. In particular, in Ref. 3 (I) matrix elements of $\theta_{\mu\nu}$ between the octet baryon states were saturated with f, f', and P assuming that the coupling constants go like $1/m_B$ (m_B =baryon mass) within the SU_3 multiplet, apart from the Clebsch-Gordan coefficients. We obtained the Gell-Mann–Okubo (GMO) mass formula, D/F ratio for tensor-meson–baryon–baryon couplings, values of P- and f-nucleon-nucleon couplings, all in good agreement with the experiments. In this work we apply a similar procedure to the matrix elements of $\theta_{\mu\nu}$ between vector-meson states and find very interesting consequences for the tensor couplings and total cross sections of the old (ρ, K^*, ω, ϕ) and the new (ψ, ψ', D^*, etc.) vector mesons.

II. TENSOR-MESON AND POMERON DOMINANCE

The matrix elements of $\theta_{\mu\nu}$ between two identical vector-meson states contain six form factors.[4] In the present work we will be concerned with only one of these:

$$\langle V_2(p_2)|\,\theta_{\mu\nu}|\,V_1(p_1)\rangle = \frac{G_1(q^2)}{2}\,\epsilon_1\cdot\epsilon_2 P_\mu P_\nu + \cdots , \tag{1}$$

where $P = p_1 + p_2$, $q = p_1 - p_2$. ϵ_1 and ϵ_2 are the polarization vectors of the vector mesons. The condition

$$\left\langle V(\vec{p}=0)\middle| \int \theta_{00}(x)\, d^3x \middle| V(\vec{p}=0)\right\rangle = m_V\langle V|V\rangle \tag{2}$$

gives $G_1(0) = -1$.

Similarly the tensor-meson matrix element between the vector-meson states is given by four coupling constants.[5] Again we will need only one of these:

$$\langle V(p_2)|T|\,V(p_1)\rangle = \frac{g_{TVV}}{2m_T}\left(\frac{\overline{m}^2}{m_V{}^2}\right)\epsilon_1\cdot\epsilon_2 P_\mu P_\nu \epsilon^{\mu\nu} + \cdots . \tag{3}$$

$\epsilon^{\mu\nu}$ and m_T are respectively the polarization tensor and the mass of the tensor meson. m_V is the mass of the vector meson and $\overline{m}$ is some average mass. The factor $\overline{m}^2/m_V{}^2$ is explicitly extracted from the coupling constants. g_{TVV} will be assumed to obey SU_3 symmetry relations.[6] The tensor-meson couplings to $\theta_{\mu\nu}$ are defined by

$$\langle T|\,\theta_{\mu\nu}|\,0\rangle = m_T{}^3 g_T \epsilon_{\mu\nu} . \tag{4}$$

As in I and Ref. 2, we saturate the form factor $G_1(0)$ with f, f' (or singlet f_1 and octet f_8), and P. Now the nature of the Pomeron has remained quite mysterious over the years. For our purpose we treat it as a factorizable SU_3-singlet Regge pole with a linearly rising trajectory ($\alpha_P = 1 + \alpha'_P t$), and the contribution to G_1 is evaluated by introducing a spin-2 particle with mass $M_P = 1/\sqrt{\alpha'_P}$. The singlet nature and factorization are probably correct within about 20%. To obtain cross sections, the spin-2 particle pole will be Reggeized, so the actual existence of such a particle may not be crucial. The small rise in total cross sections found at laboratory energies greater than about 200 GeV could be built in if necessary by taking $\alpha_P(0)$ to be slightly larger than 1. Such a procedure has been followed by several authors recently in their fits, and the fundamental problem remains common to many such approaches. At any rate we regard the results obtained here and in I as *a posteriori* justification for such an effective parametrization of the Pomeron contribution.

Then, assuming a D-type SU_3-symmetric coupling for the vector–vector–tensor-octet vertex, saturation of $G_1(0)$ leads to the following relations:

$$\frac{m_\rho^2}{\overline{m}^2} = g_P g_{P\rho\rho} + g_1 g_{1\rho\rho} + g_8 g_{8\rho\rho}, \quad (5)$$

$$\frac{m_{K^*}^2}{\overline{m}^2} = g_P g_{P\rho\rho} + g_1 g_{1\rho\rho} - \frac{g_8}{2} g_{8\rho\rho}, \quad (6)$$

$$\frac{m_{\omega_8}^2}{\overline{m}^2} = g_P g_{P\rho\rho} + g_1 g_{1\rho\rho} - g_8 g_{8\rho\rho}, \quad (7)$$

$$\frac{m_{\omega_1}^2}{\overline{m}^2} = g_P g_{P\omega_1\omega_1} + g_1 g_{1\omega_1\omega_1}, \quad (8)$$

$$\frac{m_{\omega_1\omega_8}^2}{\overline{m}^2} = g_8 g_{8\omega_1\omega_8}. \quad (9)$$

Here $g_{1\rho\rho}(g_1)$ and $g_{8\rho\rho}(g_8)$ are respectively the singlet and octet tensor-meson couplings to the ρ meson[7] ($\theta_{\mu\nu}$). ω_1 and ω_8 are the singlet and the octet components of the ω and ϕ mesons. Note that Eqs. (5), (6), and (7) automatically satisfy the GMO mass formula

$$4m_{K^*}^2 = 3m_{\omega_8}^2 + m_\rho^2. \quad (10)$$

Of course, it should be stated that the (mass)^2 in Eq. (10) arises essentially from the definitions of the coupling constants in Eq. (3).

Similar equations can be written for the diagonal representation with physical masses m_ϕ^2, m_ω^2:

$$m_\phi^2/\overline{m}^2 = g_P g_{P\phi\phi} + g_1 g_{1\phi\phi} + g_8 g_{8\phi\phi}, \quad (11)$$

$$m_\omega^2/\overline{m}^2 = g_P g_{P\omega\omega} + g_1 g_{1\omega\omega} + g_8 g_{8\omega\omega}. \quad (12)$$

The simplest assumption would be that the same matrix

$$\begin{pmatrix} \cos\theta_V & \sin\theta_V \\ -\sin\theta_V & \cos\theta_V \end{pmatrix}$$

which diagonalizes m^2 in (7), (8), and (9) also diagonalizes all the couplings of P, 1, and 8 separately. A more complicated possibility would be that the mixing angles are different and diagonalization is achieved by conspiracy between different terms. We consider the first alternative. Then it readily follows that

$$g_{P\phi\phi} = g_{P\omega\omega} = g_{P\omega_1\omega_1} = g_{P\omega_8\omega_8}, \quad (13)$$

$$g_{1\phi\phi} = g_{1\omega\omega} = g_{1\omega_1\omega_1} = g_{1\omega_8\omega_8}, \quad (14)$$

$$g_{8\phi\phi} = -g_{8\omega\omega}\cot^2\theta_V = g_{8\omega_8\omega_8}\left(\frac{\cos^2\theta_V}{\cos 2\theta_V}\right). \quad (15)$$

We have used the fact that $g_{P\omega_1\omega_8} = g_{1\omega_1\omega_8} = g_{8\omega_1\omega_1} = 0$. Then

$$m_{\omega_1}^2 + m_{\omega_8}^2 = m_\phi^2 + m_\omega^2 \quad (16)$$

and

$$\frac{m_{\omega_8}^2 - m_{\omega_1}^2}{m_\phi^2 - m_\omega^2} = \cos 2\theta_V, \quad (17)$$

as it should be.

We need one more input to solve the equations for the couplings. In accordance with the Okubo-Zweig-Iizuka (OZI) rule[8] we assume that $g_{f'\rho\rho} = 0$. The OZI rule forbids couplings between particles which are supposed to contain only strange (or charmed) quarks with the ones without these quarks. It seems to be approximately correct for couplings such as $\phi\rho\pi$, $f'\pi\pi$, $f'NN$, etc. In the quark model nonvanishing values of these couplings (violation of the OZI rule) may just mean some small admixture of the other kind of quarks. Later we will consider deviation from the OZI rule. At the present time, we obtain

$$g_{f\rho\rho} = \frac{g_{1\rho\rho}}{\cos\theta_T} = \frac{g_{8\rho\rho}}{\sin\theta_T}. \quad (18)$$

From Eqs. (5), (6), and (18) one finds

$$g_{f\rho\rho} = \frac{2}{3g_8}\,\frac{m_\rho^2 - m_{K^*}^2}{\overline{m}^2}\,\frac{1}{\sin\theta_T}. \quad (19)$$

Now, as in I, the principle of universality of scalar and tensor couplings to the stress tensor[9] fixes g_f, $g_{f'}$, g_P and hence g_1 and g_8 for a given mixing angle θ_T. We take the values of these constants from I, so these are *not* new parameters here. $g_{f\rho\rho}$ is then determined from (19) and $g_{P\rho\rho}$, $g_{P\phi\phi}$, $g_{P\omega\omega}$ from (5), (13), and (18).

Other couplings such as $g_{f\omega\omega}$, $g_{f'\phi\phi}$, etc. are now readily given by (14) and (15). Since $g_{f'\rho\rho} = 0$ and $g_{8\omega_8\omega_8} = -g_{8\rho\rho}$ by SU_3, we get

$$g_{f\omega\omega} = \left(\cos^2\theta_T + \frac{\sin^2\theta_T \sin^2\theta_V}{\cos 2\theta_V}\right) g_{f\rho\rho}, \quad (20)$$

$$g_{f'\phi\phi} = -\frac{\sin 2\theta_T}{2}\,\frac{3\cos^2\theta_V - 1}{\cos 2\theta_V}\, g_{f\rho\rho}. \quad (21)$$

When $\theta_V = \theta_T = 35.3°$ (ideal), (20) and (21) reduce to the well-known relations $g_{f\omega\omega} = g_{f\rho\rho}$ and $g_{f'\phi\phi} = -\sqrt{2}\, g_{f\rho\rho}$. Now we consider some numerical values of the coupling constants in this approach. Taking $g_f = 0.076$, $g_{f'} = -0.064$, and $g_P = 0.097/\sqrt{\alpha_P'}$ (α_P' in GeV^{-2}) from paper I, we find, for ideal f-f' mixing $\theta_T = 35.3°$,

$$g_{f\rho\rho} = 38.84, \quad g_{P\rho\rho} = g_{P\omega\omega} = g_{P\phi\phi} = 22.02/\sqrt{\alpha_P'}. \quad (22)$$

These are independent of the mixing angle θ_V. As in I, however, the results are sensitive to the value of θ_T. This happens because of the large cancellation between g_f and $g_{f'}$ terms in the equation for g_8. As we have used the OZI rule, it is perhaps more appropriate (although not necessary) to use the ideal (canonical) value for θ_T. But for the sake of completeness, we quote the values for $\theta_T = 31°$ (which is in the range predicted by the mass formulas of the tensor mesons). We have

$$\theta_T = 31° \rightarrow g_{f\rho\rho} = 23.01, \quad g_{P\rho\rho} = 9.63/\sqrt{\alpha_P'} . \quad (23)$$

The estimation of deviation from the OZI rule will be very model-dependent. For the ϕ meson the OZI suppression factor $g_{\phi\rho\pi}/g_{\omega\rho\pi}$ is believed to be typically about $\frac{1}{10}$. If, in the case of f', there is a similar factor, then $g_{f'\rho\rho}/g_{f\rho\rho} = \frac{1}{10}$. Solving the equations with this input, we find

$$\theta_T = 35.3° \rightarrow g_{f\rho\rho} = 34.02, \quad g_{P\rho\rho} = 16.01/\sqrt{\alpha_P'} . \quad (24)$$

In this way all the coupling constants can be determined in terms of masses and α_P'. Next we discuss applications of these results.

III. DECAYS OF TENSOR MESONS

From the above values of g_{fVV} and $g_{f'VV}$, all the other g_{TVV} couplings also can be readily determined by using SU_3 symmetry. These couplings become relevant in the models of decays of tensor mesons. Since this involves a detailed program by itself, we hope to present such calculations separately in the future. Here we just make a few remarks based on comparison with already existing works. In Ref. 4, Renner studied tensor dominance of vector mesons using f and f' intermediate states and determined $g_{f\rho\rho}$. Then using vector dominance he related the other three couplings to $g_{f\rho\rho}$. In our notation he found $g_{f\rho\rho} = 9.44$, which is smaller by a factor of about 2.5 to 4 when compared with our values [Eqs. (22), (23), and (24)]. He calculated radiative decay widths of f mesons, for which, unfortunately, as yet no experimental data are available. But some time in the future the situation could change. In a recent work Levy, Singer, and Toaff[10] consider dual amplitudes for pseudoscalar-vector scattering and obtain g_{TVV} couplings. In spite of the fact that their model is entirely different from that of Renner, the values of the dominant couplings obtained were very close in the two models. It appears that the different values obtained for $g_{f\rho\rho}$ in the present model stems from the breaking of duality by the introduction of the Pomeron. With their values of $g_{f\rho\rho}$ (comparable to Renner's) the authors of Ref. 10 calculate the decay width of $f \rightarrow \rho^0\pi^+\pi^-$ to be 0.49 MeV. The experimental decay width for $f \rightarrow \pi^+\pi^-\pi^+\pi^-$ is given to be 6.2 ± 1.5 MeV. Even granting that the latter width includes more than just $\rho\pi\pi$ events, there is a discrepancy by a factor of about 6 to 10. It is very interesting that the larger value of $g_{f\rho\rho}$ required to remove this discrepancy is indeed provided by the present model. Similarly, Γ_{theory} for $A_2 \rightarrow \omega\pi^+\pi^-$ comes out to be smaller than Γ_{expt} by a factor of about 4 in Ref. 10. Also, in another recent work Novikov and Eidelman[11] estimate $g_{f\rho\rho}$ by assuming that the entire $f \rightarrow 2\pi^+2\pi^-$ decay proceeds through $\rho^0\rho^0$ intermediate states, and they obtain a value which is about a factor of 2 larger than that of Renner. The motivation in Ref. 11 was to estimate the charge asymmetry of π mesons in the $e^+e^- \rightarrow \pi^+\pi^-$ reaction, for which $g_{f\rho\rho}$ is clearly relevant. Thus the coupling constants g_{TVV} obtained here, which are larger than the ones determined by dual or f-f' tensor-dominance models, seem to be required by the experimental data. Now we consider the vector-meson-nucleon total cross sections.

IV. VECTOR-MESON-NUCLEON CROSS SECTIONS

The coupling constant g_{PVV} is clearly relevant to the calculation of vector-meson-nucleon total cross sections for which data are becoming available. We evaluate the cross sections in a very simple model in which the spin-2 contribution is Reggeized by assuming structureless residue functions. We consider only the asymptotic Pomeron contribution, although the present model also makes definite predictions for the secondary contributions from f and f'.

Let $A(s,t)$ be the spin-averaged amplitude for V-N scattering $[V_1(p_1,\epsilon_1) + N_1(q_1) \rightarrow V_2(p_2,\epsilon_2) + N_2(q_2)]$ as $s \rightarrow \infty$. Only the first term in the vertex function (3) contributes as $t \rightarrow 0$ ($p_1 = p_2$, $\epsilon_1 = \epsilon_2$). The PNN vertex is taken from (I) [Eq. (3)],

$$\langle N(q_2)|T|N(q_1)\rangle = \frac{g_{PNN}}{4m_T}\left(\frac{\overline{m}_B}{m_N}\right)\epsilon^{\mu\nu}\bar{u}(q_2) \times (\gamma_\mu Q_\nu + \gamma_\nu Q_\mu)u(q_1), \quad (25)$$

where $Q = q_1 + q_2$. Then

$$A(s,t) = \frac{g_{PVV}\,g_{PNN}}{m_P^2}\left(\frac{\overline{m}_B}{m_N}\right)\left(\frac{\overline{m}}{m_V}\right)^2 \frac{2s^2}{m_P^2 - t} . \quad (26)$$

Reggeizing

$$\frac{s^2}{m_P^2 - t} \rightarrow \frac{-\pi\alpha_P' s_0^2}{2}\,\frac{(1 + e^{-i\pi\alpha_P})}{\sin\pi\alpha_P}\left(\frac{s}{s_0}\right)^{\alpha_P(t)} .$$

Now the optical theorem

$$\sigma_{VN}^{\text{tot}} = \frac{1}{s}\,\text{Im}A(s,0) \quad (27)$$

gives

$$\sigma_{VN}^{\text{tot}} = \frac{\pi}{2}\,s_0\alpha_P'(\sqrt{\alpha_P'}\,g_{PVV})(\sqrt{\alpha_P'}\,g_{PNN})\left(\frac{\overline{m}_B}{m_N}\right)\left(\frac{\overline{m}}{m_V}\right)^2 , \quad (28)$$

where we have used $M_P^2 = 1/\alpha_P'$.

Similarly, the nucleon-nucleon total cross section is given by

$$\sigma_{NN}^{\text{tot}} = \frac{\pi}{2} s_0 \alpha_P' (\sqrt{\alpha_P'} g_{PNN})^2 \left(\frac{\overline{m}_B}{m_N}\right)^2 . \tag{29}$$

The g's have been combined with $\sqrt{\alpha_P'}$ since their product is determined by our tensor-dominance relations. As usual $s_0 = 1$ GeV^2. All the coupling constants have been already determined, so α_P' remains the only free parameter. This can be fixed from, say, σ_{NN}^{tot}. Then Eq. (28) gives absolute predictions for σ_{VN}^{tot}.

So far we have considered only the well established SU_3 nonet of vector mesons (ρ, K^*, ω, ϕ). Recently, however, some new vector mesons such as ψ, D^*, ψ', etc. have been discovered. All of these could be part of some SU_4 multiplets such as 1, 15, etc. One can extend the present formalism to such cases. However, in view of the current uncertainty in SU_4 mass formulas we limit our discussion to some general remarks. By the OZI rule presumably f and f' will not contribute to the mass equation for, say, the ψ meson, but the corresponding charmed tensor mesons will. Their contributions could be similarly evaluated. Now from (13) we see that the values of $g_{P\rho\rho}$, $g_{P\omega\omega}$, and $g_{P\phi\phi}$ are the same in spite of mass breaking and ϕ-ω mixing. So it is plausible that $g_{P\psi\psi}$ (or $g_{PD^*D^*}$) will also have comparable value. The main difference in the effective coupling will then arise from the factor $1/m_V^2$. An immediate interesting consequence from Eq. (28) is that σ_{VN} will go like $1/m_V^2$. This fact seems to be consistent with the experiments. Vector-meson–nucleon total cross sections have been determined by studying the A dependence of the diffractive photoproduction of vector mesons on different nuclear targets. There are a number of uncertainties, but the typical current values are[12]

$$\sigma_{\rho N} = \sigma_{\omega N} \approx 25\text{–}30 \text{ mb}, \quad \sigma_{\phi N} \approx 13 \text{ mb},$$
$$\sigma_{\psi N} = 3.5 \pm 0.8 \text{ mb}. \tag{30}$$

Since $m_\rho^2/m_\omega^2 = 0.97$, $m_\rho^2/m_\phi^2 = 0.57$, and $m_\rho^2/m_\psi^2 = 0.062$, the agreement is very good, considering the simplicity of the model. In particular, the present model does explain the smaller value of $\sigma_{\phi N}$ and a drastically smaller value for $\sigma_{\psi N}$ as compared to $\sigma_{\rho N}$. Similar arguments would lead to $\sigma_{D^*N}/\sigma_{\rho N} \approx 0.15$ and $\sigma_{\psi' N}/\sigma_{\rho N} \approx 0.044$, assuming that P couplings without the mass factors are the same. It will be interesting to test these predictions when data become available.

While this work was being completed, we became aware of a recent work by Carlson and Freund[13] in which such a $1/m_V^2$ dependence is obtained from the assumptions of a tensor-meson-dominated Pomeron,[14] exchange degeneracy, and equality of slopes of the vector-meson trajectories ($\alpha_\rho' = \alpha_\phi' = \alpha_\psi'$). However, in our model such a dependence comes from an entirely different assumption of quadratic mass formulas for vector mesons. Also in the tensor-meson-dominated Pomeron model, the following equality is obtained:

$$\frac{g_{f\rho\rho}}{g_{P\rho\rho}} = \frac{g_{fNN}}{g_{PNN}} . \tag{31}$$

Comparing the values of f and P couplings found in this paper with the values from I, we find that the equality is satisfied very well by the couplings for any value of θ_T. In our model, however, the couplings are determined by the masses. Looking at the equations, it is seen that the result comes out because the experimental masses satisfy the relation $\overline{m}^2/m_\rho^2 = \overline{m}_B/m_N$ to an extremely good accuracy [$\overline{m}^2$ and $\overline{m}_B$ are, respectively, the average (mass)^2 of the vector octet and the average mass of the baryon octet and not just the scale factors introduced in Eqs. (3) and (25)]. Thus, although the results are similar, the two models obtain them in an entirely different manner. In the present model there is no constraint on the Pomeron couplings except the satisfaction of the mass relations.

Now, relations between cross sections are given by models such as the quark model. But the present approach also gives the absolute magnitude of the cross sections. To give some numerical examples, let $\theta_T = 35.3°$ ($g_{f'\rho\rho} = g_{f'NN} = 0$). Then Eq. (19) of I gives $g_{PNN} = 21.6/\sqrt{\alpha_P'}$. Taking $g_{P\rho\rho}$ from Eq. (22) of the present work we have

$$\sigma_{\rho N} = 438.3\alpha_P' \text{ mb } (\alpha_P' \text{ in GeV}^{-2}),$$
$$\sigma_{NN} = 428.5\alpha_P' \text{ mb}. \tag{32}$$

Taking σ_{NN} to be 39 mb we have $\alpha_P' = 0.09$ GeV^{-2}. Hence,

$$\sigma_{\rho N} = 39.9 \text{ mb},$$
$$\sigma_{\omega N} = 38.7 \text{ mb},$$
$$\sigma_{\phi N} = 22.7 \text{ mb},$$
$$\sigma_{\psi N} = 2.5 \text{ mb}. \tag{33}$$

On the other hand, if we have $g_{f'\rho\rho}/g_{f\rho\rho} = \frac{1}{10}$, while still taking $g_{f'NN} = 0$ and $\theta_T = 35.3°$, Eq. (24) gives

$$\sigma_{\rho N} = 29.0 \text{ mb},$$
$$\sigma_{\omega N} = 28.1 \text{ mb},$$
$$\sigma_{\phi N} = 16.5 \text{ mb},$$
$$\sigma_{\psi N} = 1.8 \text{ mb}. \tag{34}$$

Also, because the ratios in (31) remain equal as we change θ_T, $\sigma_{\rho N}/\sigma_{NN}$ has the same value for $\theta_T = 35.3°$ and $31°$; the only difference is that $\sigma_{NN} = 39$ mb would need $\alpha_P' = 0.48$ GeV^{-2} in the second case.

In the case of OZI violation, even if $g_{f'\rho\rho}/g_{f\rho\rho} = g_{f'NN}/g_{fNN}$, $\sigma_{\rho N}$ will be smaller than σ_{NN} if the value of α_P' for the vector case is smaller than that in the nucleon case. Although this is not particularly appealing for the interpretation of a Pomeron trajectory, it should be noted that, in data fitting,[12] the α_P' obtained from photoproduction of vector mesons is found to be smaller than the one obtained from the nucleon-nucleon scattering. In addition, some deviations from the universal values of g_f, $g_{f'}$, g_P, and F_σ (see I) will also result in changes in absolute magnitudes of the cross sections.

It is also interesting to note that the linear mass formulas do not work. If we use the factor $(\overline{m}/m_V)$ in Eq. (3) instead of $(\overline{m}/m_V)^2$, we find that

$$\sigma_{\rho N} : \sigma_{\phi N} : \sigma_{\psi N} = \frac{1}{m_\rho} : \frac{1}{m_\phi} : \frac{1}{m_\psi} = 4 : 3 : 1 , \qquad (35)$$

which is in clear contradiction with the data. In addition, the ratio $\sigma_{\rho N}/\sigma_{NN}$ comes out to be 0.3, which is also completely off. Thus we can regard the present results as supporting the case for quadratic mass formulas. Because of the ω-ϕ mixing problem, from masses alone one cannot distinguish between the linear and the quadratic forms.

In the above we have considered σ_{VN} and σ_{NN}. However, recently, some data on Σ-N and Ξ-N scattering have also become available.[15,16] The model in I gives for the asymptotic (Pomeron) contributions

$$\frac{\sigma_{\Sigma N}}{\sigma_{NN}} = \frac{m_N}{m_\Sigma} = 0.78 \text{ and } \frac{\sigma_{\Xi N}}{\sigma_{NN}} = \frac{m_N}{m_\Xi} = 0.71 . \qquad (36)$$

The currently available data[15,16] indicate that

$$\frac{\sigma_{\Sigma p}}{\sigma_{pp}} = 0.85\text{–}0.87 \text{ and } \frac{\sigma_{\Xi p}}{\sigma_{pp}} \sim 0.7 . \qquad (37)$$

Thus the data are quite consistent with our prediction that $\sigma_{\Xi N} < \sigma_{\Sigma N} < \sigma_{NN}$, and even the $1/m_B$ dependence also could be approximately true.

V. CONCLUDING REMARKS

It might be argued that, because of the relative crudeness with which the Pomeron contribution has been handled, the striking numerical results may not have particular significance. Even if this is true, some general results should remain valid. In particular, the $1/m_V^2$ behavior of σ_{VN} and the fact that σ_{NN} and σ_{VN} come out to have reasonable magnitude with the usually accepted small values of α_P' (<0.5 GeV^{-2}) should be regarded as successes of this approach. Another significant prediction lies in the larger value of g_{TVV} obtained in the present work, as compared to the dual or non-Pomeron tensor-dominance models. As we have mentioned in the text, the data on tensor-meson decays seem to require such larger values. Also, as mentioned in Sec. IV, $\sigma_{BN} \propto 1/m_B$ (baryon mass) may be also approximately true. The results of this paper taken together with paper I lead us to conclude that the dominant matrix elements of $\theta_{\mu\nu}$ between vector mesons and baryons can be rather well saturated with the known tensor mesons and the Pomeron without requiring any subtraction or some hypothetical mesons. Furthermore, this procedure does provide insight into the dynamics of symmetry breaking in masses and leads to a number of experimentally verifiable predictions. As we have already remarked in I, the saturation procedure does not work in the case of pseudoscalar mesons because of the large amount of symmetry breaking in masses. The mass relations probably need subtraction constants or extra tensor mesons. In Ref. 2, the masses were absorbed in the definition of the coupling constants and the satisfaction of mass formulas was not required. Then, using nonuniversal values for g_f, g_P, etc. consistent solutions were obtained. In Ref. 3 (I) and here satisfaction of the mass formulas has been the starting point. It should be noted that similar difficulty for the pseudoscalar case appears in the study of scalar dominance.[17]

Finally, as for the role of the Pomeron in the present saturation scheme, one can simply regard it as the contribution which remains after the usual tensor-meson-pole contributions are taken out from the particle-antiparticle cross-channel amplitude. It would then include continuum also. Of course, factorization would be difficult to understand in such a case. However, possibly an effective pole could somehow take care of such contributions. In such a scheme, then, masses of the particles could be consistently expressed as dynamical quantities related to the tensor-meson and Pomeron-exchange forces.

ACKNOWLEDGMENTS

The author wishes to thank Professor S. Mandelstam and Professor J. D. Jackson for their kind hospitality at the Physics department and the Lawrence Berkeley Laboratory of University of California at Berkeley, where this work was done. He is also thankful to Professor M. Suzuki for helpful discussions and to the NSF for support.

APPENDIX

Here we give the complete matrix elements for $\theta_{\mu\nu}$ [Eq. (1)] and T [Eq. (3)]. A factor of 2 is introduced for convenience. For $\theta_{\mu\nu}$ we have

$$
\begin{aligned}
2\langle V_2(p_2)|\,\theta_{\mu\nu}|\,V_1(p_1)\rangle = {} & G_1(q^2)\epsilon_1\cdot\epsilon_2 P_\mu P_\nu + G_2(q^2)(\epsilon_1\cdot P)(\epsilon_2\cdot P)P_\mu P_\nu \\
& + G_3(q^2)[(\epsilon_1\cdot P)\epsilon_{2\mu}P_\nu + (\epsilon_1\cdot P)\epsilon_{2\nu}P_\mu + (\epsilon_2\cdot P)\epsilon_{1\mu}P_\nu + (\epsilon_2\cdot P)\epsilon_{1\nu}P_\mu] \\
& + G_4(q^2)[(\epsilon_1\cdot q)\epsilon_{2\mu}q_\nu + (\epsilon_1\cdot q)\epsilon_{2\nu}q_\mu + (\epsilon_2\cdot q)\epsilon_{1\mu}q_\nu + (\epsilon_1\cdot q)\epsilon_{1\nu}q_\mu \\
& \qquad - 2(\epsilon_1\cdot q)(\epsilon_2\cdot q)g_{\mu\nu} - q^2(\epsilon_{1\mu}\epsilon_{2\nu} + \epsilon_{2\mu}\epsilon_{1\nu})] \\
& + G_5(q^2)(\epsilon_1\cdot\epsilon_2)(q_\mu q_\nu - q^2 g_{\mu\nu}) + G_6(q^2)(\epsilon_1\cdot P)(\epsilon_2\cdot P)(q_\mu q_\nu - q^2 g_{\mu\nu}).
\end{aligned}
$$

The matrix element for T is given by

$$\langle V(p_2)|T|\,V(p_1)\rangle = \tfrac{1}{2}\epsilon^{\mu\nu}A_{\mu\nu},$$

where

$$
\begin{aligned}
A_{\mu\nu} = {} & \frac{g^{(1)}_{TVV}}{m_T}(\epsilon_1\cdot\epsilon_2)P_\mu P_\nu + \frac{g^{(2)}_{TVV}}{m_T{}^3}(\epsilon_1\cdot P)(\epsilon_2\cdot P)P_\mu P_\nu \\
& + \frac{g^{(3)}_{TVV}}{m_T}[(\epsilon_1\cdot P)\epsilon_{2\mu}P_\nu + (\epsilon_1\cdot P)\epsilon_{2\nu}P_\mu + (\epsilon_2\cdot P)\epsilon_{1\mu}P_\nu + (\epsilon_2\cdot P)\epsilon_{1\nu}P_\mu] \\
& + \frac{g^{(4)}_{TVV}}{m_T}[(\epsilon_1\cdot q)\epsilon_{2\mu}q_\nu + (\epsilon_1\cdot q)\epsilon_{2\nu}q_\mu + (\epsilon_2\cdot q)\epsilon_{1\mu}q_\nu + (\epsilon_2\cdot q)\epsilon_{1\nu}q_\mu - 2(\epsilon_1\cdot q)(\epsilon_2\cdot q)g_{\mu\nu} - q^2(\epsilon_{1\mu}\epsilon_{2\nu} + \epsilon_{1\nu}\epsilon_{2\mu})].
\end{aligned}
$$

In the present paper only $g^{(1)}_{TVV}$ is needed and the superscript is dropped.

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*This work has been supported in part by the National Science Foundation.

† Permanent address. On sabbatical leave during fall semester 1976.

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[4]See, for example, B. Renner, Nucl. Phys. B30, 634 (1971). The complete matrix element is given in the Appendix.

[5]The complete matrix element for this case is also given in the Appendix.

[6]As was emphasized in I, the question as to which coupling constants obey SU_3 symmetry is entirely a dynamical one and cannot be settled *a priori*, without appealing to the experiments. The definition (3) will give rise to GMO mass formulas for (mass)^2 of the vector mesons. Previous authors such as Renner in Ref. 4 did not define their couplings in this manner and accordingly did not get the mass formulas. If we pull out $(\overline{m}/m_V)$, linear mass formulas will be obtained. This fact has nothing to do with the kind of normalization one uses for the states. As for the "folklore" that SU_3 is broken only by masses and the coupling constants are SU_3-invariant, we have to say that it has been verified in very few cases and then only very approximately. The literature is full of cases where such mass factors have to be provided by hand. In addition, in many cases such as the present one the Lagrangian one writes down in a "natural" way has dimensional coupling constants, which need mass factors to make them dimensionless. Thus there is an unavoidable ambiguity which can only be settled dynamically. In our case after extracting $m_V{}^2$ we have to introduce $\overline{m}^2$, which we take to be 0.728 GeV^2 (average mass^2 of the vector octet). However, it can be chosen as completely arbitrary since only the products of g's with $\overline{m}^2$ will appear in any application.

[7]We use the convention $f = f_1\cos\theta_T + f_8\sin\theta_T$, $f' = -f_1\sin\theta_T + f_8\cos\theta_T$, $\omega = \omega_1\cos\theta_V + \omega_8\sin\theta_V$, $\phi = -\omega_1\sin\theta_V + \omega_8\cos\theta_V$.

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also used similar models to explain suppression of $\sigma_{\phi N}$ and $\sigma_{\psi N}$ relative to $\sigma_{\rho N}$. Some of these are: Chan Hong-Mo, J. Kwiecinski, and R. G. Roberts, Phys. Lett. 60B, 367 (1976); C. Rosenzweig and G. F. Chew, *ibid.* 58B, 93 (1975); T. Inami, *ibid.* 56B, 291 (1975); N. Papadopoulos, C. Schmid, C. Sorensen, and D. M. Webber, Nucl. Phys. B101, 189 (1975). It is also interesting to note that an entirely different model, the generalized vector-dominance model, also gives $1/m_V{}^2$ dependence of σ_{VN}^{tot} (transverse part) when scaling behavior is imposed on the e^+e^- annihilation cross section and the transverse virtual-photon total cross section. See, for example, S. Chavin and J. D. Sullivan, Phys. Rev. D 13, 2990 (1976), which gives earlier references.

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$$\frac{b_{\Xi^- p}}{b_{pp}} = \frac{\sigma_{\Xi^- p}^{\text{tot}}}{\sigma_{pp}^{\text{tot}}}$$

given in this reference. This relation has been shown to be consistent with the data on $\Sigma^- p$ scattering.

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