### SPIN AND MASS DEPENDENCE OF MODELS FOR $\psi$ -PHOTOPRODUCTION \*

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## ABSTRACT

The spin and vector meson mass-dependence of phenomenological and constituent models for  $\gamma N \rightarrow \psi N$  is investigated. Our main interest centers on the influence of the large vector meson mass on s-channel helicity conservation at asymptotic and SLAC energies. The helicity amplitudes for photoproduction are studied in the context of several phenomenological and constituent models. In particular, in a model in which the vector meson is treated as a nonrelativistic bound state of a quark-antiquark pair, with two vector gluon exchange to the target, helicity flip is very small, but nonzero. The ratio of helicity flip to nonflip is found to be sensitive to the gluon mass in this model. Two scalar gluon exchange is found to conserve helicity asymptotically, but to flip it near threshold. In general, phenomenological models can partially account for the suppression of  $\psi$  photoproduction compared to photoproduction of the lighter vector mesons, whereas the constituent models can not.

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### I. INTRODUCTION

Following the discovery of the narrow resonances  $\psi(3.1)$  and  $\psi'(3.7)$  in  $e^+e^$ annihilation and massive lepton pair production, several models have been proposed to explain their properties.<sup>1</sup> While experiments have revealed tantalizing clues in support of a bound state interpretation of the new particles, there is still little insight into how the new constituents (c-quarks) interact with the hadrons made out of conventional SU<sub>3</sub> quarks (q-quarks), so that additional experimental constraints are needed. One such constraint, the spin dependence of  $\psi$ -photoproduction, is analyzed in the present work.

In comparison to  $\rho$ -photoproduction,  $\psi$ -photoproduction is suppressed, but shows diffractive characteristics.<sup>2</sup> We therefore investigate the following questions concerning  $\psi$ -photoproduction:

(i) Is s-channel helicity conserved?

(ii) What causes the suppression?

(iii) Are all vector mesons produced by the same mechanism?

(i) Data for  $\rho^{0}$  and  $\omega$ -photoproduction in the region  $-t \leq 1 \text{ GeV}^{2}$  (s  $\leq 20 \text{ GeV}^{2}$ ) show that the dominating production process is s-channel helicity conserving (SCHC) and that there may be SCHC violation at the 10% level.<sup>3</sup> The diffractive s- and t-dependence of these processes therefore suggests that SCHC is a general feature of diffractive scattering at high energies, as has been found to be the case in a number of other reactions.<sup>4</sup> Consequently, it is interesting to ask whether SCHC, as a characteristic feature of diffraction, will carry over to  $\psi$ photoproduction. The answer to this question does not seem trivial to us for the following reason: the masses of the initial and final state particles differ to such an extent that one may question whether this process is essentially elastic. At SLAC energies, where most of the data on  $\gamma N \rightarrow \psi N$  have been taken, the  $(\psi-\text{mass})^{2}$  is comparable to  $s \approx 30 \text{ GeV}^2$ . One might expect effects due to the nonasymptotic energy; for instance  $|t_{\min}|$  is no longer at 0.

(ii) The different nature of the  $\psi$ -particles with respect to their creation and decay raises the question whether conventional schemes still apply. If they are of hadronic nature, as we shall assume here, what causes the suppression of  $\psi$ photoproduction? Once one assumes that  $\psi$ -particles are composed of heavy spin-1/2 constituents (c-quarks), one has to specify their interaction with the q-quarks. The Okubo-Zweig-Iizuka (OZI) rule<sup>5</sup> does not allow such interaction, which is commonly thought to be the reason for the suppressed rates. The simplest explanation in the Regge framework is to assume conventional Pomeron exchange—but why are  $\psi$ -P couplings then smaller than  $\phi$ -P or  $\rho$ -P? Following the suggestion by Low and Nussinov<sup>6</sup> that the Pomeron could be understood as a two (or more) gluon exchange process, we shall pursue the consequences of the simplest model for  $\psi$ -photoproduction in the framework of Quantum Chromodynamics (QCD). Alternatively, we might assume that OZI-rule violating transitions are mediated by gluons or sequential poles on the first Pomeron-daughter trajectory.<sup>7</sup> One might go further and assume that there is no Pomeron-like exchange at all, but that the interaction is mediated by a virtual axial vector meson A<sub>c</sub>.<sup>8</sup>

(iii) If the production mechanism is the same for all vector mesons  $\rho, \omega, \phi, \ldots$  $\psi, \psi^{\dagger}, \ldots$ , one should be able to describe  $\psi$ -production by a model which is applicable for  $\rho, \ldots$ , etc. analytically continued to the  $\psi$ -mass. It should be possible to identify common characteristics such as, for instance, the dependence on the off-shell mass of the photon, diffractive pair production and so on. Dynamically different behaviors should be explainable by the differences in the quark masses and binding energies. We have studied the above questions in several models, two of which are of phenomenological value and were originally introduced to describe  $\rho$ -photoproduction. By variation of the mass of the produced vector meson (or c-quark), we extend them to  $\psi$ -production. The assumption that vector mesons are composed of constituents leads us to consider their bound state nature and to specify their interaction with nucleons as sketched above.

Our main interest in this paper is focused on the questions:

- 1) Can spin measurements in  $\psi$ -photoproduction give information on the suppressed interaction?
- If ρ- and ψ-photoproduction are described by the same mechanism what changes may be expected due to the large ψ-mass?

The paper is organized as follows: In Section II we present the models to be investigated and discuss their motivation. If  $\psi$  is supposed to be a  $c\bar{c}$  bound-state which interacts via two-gluon exchange, a loop integration has to be performed. The spin dependence of the models we have studied and details of our analysis are discussed in Section III. In Section IV we focus on the dependence of these models on the vector meson mass and point to particular features. Section V presents our conclusions.

#### II. MODELS

In this section we present the models which will be investigated in order to gain more understanding of the questions raised in Section I. In a most naive attempt, we first apply to  $\gamma N \rightarrow \psi N$  some phenomenological models which have been quite successful in describing  $\rho$ -photoproduction. Subsequently, we assume that  $\psi$  is a bound state of two heavy quarks and discuss several models for the c-quark-hadron interaction.

### 1. Phenomenological Models

Before entering the discussion of the models we find it appropriate to briefly review the available experimental information on  $\gamma N \rightarrow \psi N$  and photoproduction of the lighter vector mesons.<sup>2</sup>

The energy dependence of the cross section for  $\gamma N \rightarrow \psi N$  shows after a short, relatively slow increase up to  $E_{\gamma} \sim 12$  GeV, a strong rise up to values  $d\sigma/dt \cong$ 15 nb/GeV<sup>2</sup> at t=t<sub>min</sub>. The curve then flattens out, but continues to rise. At FNAL energies  $\langle E_{\gamma} \rangle \sim 120$  GeV, a value around 60 nb/GeV<sup>2</sup> is reached. The slope parameter b of the exponentially decreasing t-dependence is substantially smaller for  $\psi$  photoproduction than for photoproduction of the lower-mass vector mesons:

$$b_{\psi} \sim 2 \text{ GeV}^{-2}$$
,  
 $b_{\rho} \sim 6-8 \text{ GeV}^{-2}$ 

The integrated cross section at SLAC energies is  $\sigma = 5.2 \pm .6$  nb and a new point has recently been reported from FNAL at  $\langle E_{\gamma} \rangle \sim 55$  GeV of  $\sigma = 37.5 \pm 8.2$  nb.<sup>2</sup> These data, compared with  $\rho^{0}$ -photoproduction, show a suppression factor 25 in the amplitude and consequently 600 in the cross section.

One might naively expect SCHC for  $\psi$ -photoproduction by analogy with photoproduction of the lighter vector mesons. However, such a conclusion ignores the fact that at SLAC energies,  $m_{\psi}^2 \sim 10 \text{ GeV}^2$ , is of the same order of magnitude as  $s \approx 20-30 \text{ GeV}^2$ , and the  $\psi$ N-threshold is nearby. The data for  $\sigma(\psi N)$  indicate a strong rise around  $s \approx 16 \text{ GeV}^2$  and the onset of the asymptotic region above  $s \gtrsim 30 \text{ GeV}^2$ . Our naive reasoning might also be falsified by the considerable shift of  $|t_{\min}|$  towards higher values for increasing  $m_V$ . At  $s \approx 20 \text{ GeV}^2$  typical values are: for  $m_V = 1 \text{ GeV}$ ,  $|t_{\min}| \approx 0$ , whereas for  $m_V = 3 \text{ GeV}$ ,  $|t_{\min}| \approx 0.4 (\text{GeV/c})^2$ . At the upper SLAC energies ( $s \approx 40 \text{ GeV}^2$ ) this latter value however reduces to  $|t_{\min}| \approx 0.1 (\text{GeV/c})^2$ . We therefore study here the influence of the large vector meson mass (in relation to s and t) in the framework of two phenomenological models for vector meson photoproduction. Complications due to nucleon spin are neglected by treating the nucleons as scalars.

# 1.1 The DH-Model<sup>23</sup>

Diffractive  $\rho$ -photoproduction and its dual extension to  $\gamma N \rightarrow \pi^+ \pi^- N$  was the main motivation for constructing this model. The amplitude was constructed under the constraints of: (a) gauge invariance, (b) asymptotic SCHC for  $\rho$ -production, (c) natural extrapolation in the  $\pi^+\pi^-$ -channel using dual amplitudes, (d) correct single- and double-Regge asymptotics in all channels. Since we are mainly interested in the photoproduction of vector mesons, we concentrate on the first two constraints. In constructing this model, the invariant expansion of Ref. 9 with two gauge constraints has been used. In this parametrization of the invariant expansion, asymptotic SCHC imposes on the invariant amplitudes A...E the constraint A=0. The three following conditions: (a) gauge invariance, (b) asymptotic SCHC, (c) Regge asymptotics, then determine almost uniquely the form of the invariant amplitudes. The asymptotic form of the helicity amplitudes is

$$T(1, 1) \stackrel{s \to \infty}{\Longrightarrow} \stackrel{\alpha}{i} \stackrel{P}{s} \cdot \beta_t , \qquad (2.1)$$

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$$T(0,1) \implies i s^{\alpha} p^{-1} \frac{\sqrt{-t} m_V}{2} \beta_t , \qquad (2.2)$$

$$T(-1, 1) \implies i s^{\alpha} p^{-1} \frac{t}{2} \left[ m_V^2 + m_N^2 - t \right] \beta_t , \qquad (2.3)$$

where  $\beta_t$  is an exponentially decreasing function of t. 1.2 <u>The MW-Model<sup>24</sup></u>

This model was constructed to incorporate many of the properties believed to be relevant to current-hadronic interactions, such as (a) Mandelstam analyticity, (b) crossing symmetry, (c) scale invariance, (d) Regge behavior in all channels, (e) resonance poles on the unphysical sheet, (f) SU<sub>3</sub> structure of the currents, and (g) generalized vector meson dominance. Its application to  $\rho$ photoproduction density matrix elements is given in Ref. 10. In this model the tensor  $T^{\mu\nu}$  takes the well-known form of off-shell Compton scattering and depends on the two invariant amplitudes  $T_1$  and  $T_2$ . By assuming a Callan-Gross type relation

$$T_{1} = -\frac{(P \cdot Q)^{2}}{(k \cdot k')} \frac{1}{m_{N}^{2}} T_{2} . \qquad (2.4)$$

 $T^{\mu\nu}$  is made to depend essentially only on one invariant amplitude.

Since the density matrix elements are ratios of the helicity amplitudes, they are independent of  $T_2$ . Therefore the kinematical tensors, weighted according to the generalized Callan-Gross relation (2.4) solely determine the spin dependence of this model. Nevertheless, it is worthwhile to discuss the asymptotic behavior of the helicity amplitudes:

$$T(1,1) \stackrel{S \to \infty}{\Longrightarrow} i\left(-\frac{s}{am_V}\right)^{\alpha P} a^2 \cdot \left[2 + 4z + 3z^2\right] \beta_t \cdot \left(\frac{1}{g_V}\right) , \qquad (2.5)$$

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$$T(0, 1) \implies -i\left(-\frac{s}{am_{V}}\right)^{\alpha}P a^{2} \sqrt{z} \left[1+\frac{1}{2}z\right] \cdot \beta_{t} \cdot \left(\frac{1}{g_{V}}\right) , \qquad (2.6)$$

$$T(-1, 1) \Rightarrow -i\left(-\frac{s}{am_V}\right)^{\alpha P} a^2 z^2 \cdot \beta_t \cdot \left(\frac{1}{g_V}\right) , \qquad (2.7)$$

where  $z \equiv -t/2m_V^2$  and  $g_V \equiv em_V^2/2\gamma_V$  abbreviates the vector dominance coupling.  $\beta_t$  is an essentially t-independent function. The scale-factor (a.m<sub>V</sub>) in Eqs. (2.5)-(2.7) is a consequence of the "generalized scaling variable"

$$\omega' = 1 + x_1 x_2 (s - s_t) , \qquad (2.8)$$

where

$$x_i \equiv \left[c + \sqrt{q_t^2 - q_i^2}\right]^{-1}$$
 (i = 1, 2) (2.9)

was introduced to give the correct analyticity structure in the two current masses  $q_1^2$  and  $q_2^2$ .

## 2. Constituent Models

The models proposed so far do not give any insight into the substructure of the vector meson V. In the following we assume V to be composed of a quarkantiquark pair, bound together by a confining potential. Before presenting specific models, we define the system we shall consider and discuss our simplifying assumptions.

To begin, we assume that the c-quarks are point-like and consequently that the photon couples to them with a  $\gamma^{\mu}$ -coupling. If these quarks have an anomalous magnetic moment (and consequently extended structure) the spin characteristics will differ substantially. The large mass of the c-quark (in comparison to its binding energy) permits treatment of the cc-system as a nonrelativistic bound state whose binding forces are thought to be generated by the confinement mechanism. The consequences of such an assumption have been extensively pursued in studies of nonrelativistic bound states with a linearly growing potential at large distances and a Coulomb-potential for small distances.<sup>1</sup> In describing the interaction of this bound state system with the nucleon, we are, in principle, faced with a three (or more) body problem. However, we have reasons to believe that the cc-pair in the confined state may be considered as almost free due to the c-quark's large mass. Therefore we assume equipartition of the vector meson momentum k' among the c-quarks:  $k_1 = k_2 = k'/2$ .<sup>11</sup>

Our main interest in this section centers on the question of how the c-quarks interact with the conventional hadronic world (q-quarks). This problem has two aspects. First, the OZI-rule forbids any direct interaction between the nucleon and the  $\psi$  system. Second, data on  $\psi$ -photoproduction show diffractive behavior which indicates that the Pomeron is exchanged.

The mechanism for OZI-rule breaking is still poorly understood although several explanations have been proposed. Within the framework of QCD it is thought that multiglue states might act as mediators between the different quarks, and charmonium calculations, motivated by asymptotic freedom arguments, support such a hypothesis. Alternatively, it has been proposed that dual dynamics, in particular the 'Pomeron-diagram' (Fig. 1) might lead to an understanding of OZI-rule breaking.

As in photoproduction of the lower mass vector mesons, we assume that the Pomeron is exchanged and that its coupling to  $\psi$  is simply small. The QCD picture has led to the proposal that the Pomeron is generated by the exchange of two (or more) colored gluons between colored quarks. As an alternative we also pursue the consequences of some phenomenological Pomeron prescriptions.

In the following subsections, we elaborate on these ideas and investigate their consequences for  $\psi$ -photoproduction.

# 2.1 Gluon Exchange Models<sup>12</sup>

The successes of non-Abelian gauge theories in providing a framework for unifying weak and electromagnetic interactions in a renormalizable theory, their characteristic of becoming free for asymptotic energies and their property of possibly providing a mechanism for quark confinement has led to the postulate that hadrons consist of colored quarks which interact by the exchange of colored gluons. Dynamically such a system is described by 'Quantum Chromodynamics' (QCD). The interaction between c-quarks in  $\psi$ -photoproduction is OZI-rule violating and thus should be suppressed. In the renormalization group approach,  $\psi$ -decay is suppressed due to the smallness of the effective coupling constant at large  $Q^2$ :

$$\bar{g}^{2} = \frac{g^{2}}{1 + bg^{2} \cdot \ln \frac{Q^{2}}{\mu^{2}}} \quad . \tag{2.10}$$

This behavior has been proven for space-like  $q^2$  and subsequently arguments were given that Eq. (2.10) is also valid in the large time-like region. In the region of smaller momenta  $\sqrt{Q^2}$ , the strong coupling increases such as to provide permanent quark confinement.

Similar arguments can not be applied to the OZI-rule violating c-quark nucleon interaction in  $\psi$ -photoproduction since t is small; one can go even further and question the applicability of gluon perturbation theory in this region.

In the QCD framework one would be tempted to treat  $\psi$ -photoproduction as a multigluon exchange process with non-small coupling constants. The infinite sum of such diagrams is expected to lead to the experimentally damped tdependence and the diffractive s-dependence. However the question of suppression remains unclear. The process  $\psi^{*} \rightarrow \psi + \pi^{+}\pi^{-}$  is described by the same dual diagram as  $\psi$ -photoproduction, although in a different kinematical region. In fact it has been shown that analytic continuation of  $\gamma N \rightarrow \psi N$  via a dispersion relation and Vector Meson Dominance (VMD) does give upper limit predictions for the decay reactions in qualitative agreement with data.<sup>13</sup> The suppression here is motivated by OZI-rule violating gluon transitions, although the condition,  $Q^2$  large, for these decay channels is by no means satisfied.

A two-gluon exchange model for  $\psi$ -photoproduction in the low t-range does not seem to be particularly well justified according to the ideas sketched above and yet we consider it worthwhile to pursue the consequences of such a picture for the following reasons:

- Possible violations of SCHC at nonasymptotic energies are most likely (if at all) to be expected in the term with the smallest number of exchanged gluons.
- In the large t-region asymptotic freedom arguments are again applicable; we therefore argue that an investigation of the twogluon exchange picture is representative in the wider t-range.
- 3) One can argue that Zweig-rule forbidden decays are dominated by the exchange of gluon bound states, compound states of a few gluons only, and that the diffractive t-dependence has to be due to the confinement mechanism.
- 4) If one assumes that gluon perturbation theory is still valid, an investigation of  $\psi$ -photoproduction, as viewed in Fig. 2, starts naturally with the simplest possible diagrams.

These last two points bring us to another motivating point of view—the gluonic Pomeron. Based on the above framework of quarks and gluons, Low and Nussinov<sup>6</sup> recently suggested how to understand hadronic interactions and in particular their Regge characteristics. Figure 3 illustrates the idea. Whenever quarks come close they exchange gluons; these in turn create an internal "quark bubble" which attracts many more gluons. With the assumption of treating the gluon exchanges perturbatively, one can, to leading order of each diagram, reproduce Regge asymptotics.

The exponential t-dependence, expected for diffractive processes, is due to the quark-bag interaction in this model. Alternatively, if one gives up the quark-bag interaction, then two-gluon exchange may only be considered as an order of magnitude approximation since such diagrams show relatively little t-variation. The diffractive t-dependence expected from the sum of multigluon exchanges is still an unproved conjecture for QCD, although it is true in QED.

Without committing ourselves to either Pomeron picture, but retaining the general idea of two-gluon exchange, we investigate the spin characteristics of the model defined in diagrams (a-f) of Fig. 4. In this order of perturbation theory, this is the lowest set of Feynman diagrams compatible with photon gauge invariance; the exchanged gluons are not gauge invariant. We consider these diagrams to be the most important ones concerning its spin characteristics (possible viola-tion of SCHC) but expect that such field theoretical models describing diffractive phenomena have to take higher order contributions into account in order to obtain an exponentially decreasing t-dependence. We have mentioned earlier that bound state effects between the quarks will be ignored in this attempt.

In the formal evaluation of this model we shall first assume that the gluons are spinless and subsequently investigate the characteristics of vector-gluon exchange. The actual calculation is performed according to the Feynman rules for QED. The infrared problem is escaped by giving the gluons a finite mass in the propagator denominators. Ultraviolet divergences do not arise since the

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integral is convergent. Our calculation is performed in the framework of QCD and higher symmetry factors should in general be taken into account; however these do not come into play since the  $c\bar{c}$ -bound state as well as the nucleon are color singlet states and no color quantum numbers are exchanged.

The loop integration has been performed by using Feynman parameter integrals whose asymptotic form is obtained by use of Mellin transformation techniques.<sup>14</sup> The amplitudes describing <u>scalar gluon exchange</u> can then be given the invariant expansion

$$T_{abcd} = G \frac{2}{t-m_{\psi}^2} \sum_{i=1}^4 Q_i \cdot [W_i(s) + W_i(u)]$$
, (2.11)

$$T_{ef} = 2G \cdot \sum_{i=5}^{13} Q_i \cdot [W_i(s) + W_i(u)]$$
 (2.12)

where the  $Q_i \equiv \bar{u} r_i v$  stand for the spin factors and  $W_i(s)$  and  $W_i(u)$  are Feynman parameter integrals of the form

$$I(s,t) \equiv \int_0^1 (dx)^4 \xi(\alpha) \cdot \frac{\delta(1-\Sigma\alpha)}{[D]^2} \xrightarrow{s \to \infty} \frac{(\ln s)^m}{s^n} \cdot f_t \quad , \qquad (2.13)$$

 $\xi(\alpha)$  is a function of the  $\alpha$  parameters and  $f_t$  is a slowly varying function of t. The technical details are given elsewhere;<sup>19</sup> here we only note that the leading asymptotic behavior of the helicity amplitudes is

$$T(1, 1) \stackrel{S \to \infty}{\Longrightarrow} \frac{8\sqrt{2}G}{t-m_{\psi}^2} F_1 , \qquad (2.14)$$

$$T(0, 1) \xrightarrow{S \to \infty} \frac{G}{S} \sqrt{\frac{-t}{m_c^2}} \cdot \left[ \frac{(F_2 + iF_3)}{t - m_{\psi}^2} + iF_4 \right] , \qquad (2.15)$$

$$T(-1, 1) \xrightarrow{s \to \infty} \sqrt{2} G \frac{t}{s} \left[ \frac{iF_5}{t - m_{\psi}^2} + iF_6 \right] , \qquad (2.16)$$

where the functions  $F_i \equiv F_i(t)$  are real and slowly varying with t; they are given explicitly in Ref. 19.

In the case of <u>vector gluon exchange</u> the procedure sketched above is no longer applicable due to technical difficulties. The amplitudes therefore have the form

$$T_{abcd} = G \cdot \frac{2}{t-m_{\psi}^2} \int_0^1 (d\alpha)^4 \sum_{j=a}^d \left[ M_j \cdot I_j \right] , \qquad (2.17)$$

$$T_{ef} = 2G \cdot \int_0^1 (d\alpha)^5 \sum_{j=e}^f \left[ M_j \cdot I_j \right] , \qquad (2.18)$$

where the  $I_j$  are the Feynman parameter integrands without spin and the  $M_j$  contain all factors due to spin. Illustrative examples for diagram (a) in Fig. 4 are

$$I_{a} \equiv \frac{\delta(1-\Sigma\alpha)}{D^{2}} , \qquad (2.19)$$

$$\mathbf{M}_{a} \equiv \mathbf{M}_{a}(\mathbf{p}, \alpha) = \overline{\mathbf{u}} \left[ (\epsilon \mathbf{k}^{\dagger} - \epsilon \mathbf{k}) \mathbf{s}_{a} \right] \mathbf{v} \quad .$$
 (2.20)

 $\beta_{a}$  is a complicated function in spin space and depends on the integration parameters  $\alpha$ . By use of the computer program REDUCE we have determined the first two leading terms of  $M_{j}(p, \alpha)$  for asymptotic s-values. For each spin combination we then obtain expansions like

$$M_{j} \stackrel{s \to \infty}{\Longrightarrow} s^{n} \cdot \xi(\alpha) + \dots , \qquad (2.21)$$

where  $\xi(\alpha)$  is a linear combination of products of the integration parameters  $\alpha$ . 2.2 Sequential Pole Model

In this subsection we discuss the attempts to understand OZI-rule violation within the framework of dual dynamics. As an alternative to the explanations using gluons, presented above, Freund and Nambu<sup>7</sup> recently suggested the sequential pole model. They suppose that any OZI-rule violating decay should proceed

by the intermediary of an  $SU_4$ -singlet vector meson called  $O_V$ . The consequences of a possible  $O_S$ -meson with the quantum numbers  $J^{PC} = 0^{-+}$ , motivated by the same arguments, have been pursued by a number of authors.<sup>7</sup> As in the case  $\psi' \rightarrow \psi + \pi\pi$  one can argue that the interaction mechanism between the cc-pair and the nucleon is as drawn in Fig. 5. One of the c-quarks forms a virtual  $J^C \equiv 0^+$ -state which undergoes interaction with the q-quarks via the  $O_S$ -pole. The sequential pole is treated here as an elementary exchange although its motivation is based on the Pomeron trajectory. The amplitude for the sum of the two diagrams arising in this model may be given the form:

$$T = \frac{4G_t}{t-m_V^2} \left[ \bar{u}_2 \not k \not\in v_1 \right] , \qquad (2.22)$$

with the asymptotic form of the helicity amplitudes

$$T(1,1) \stackrel{s \to \infty}{=} (z_t)^0 \cdot \beta_t , \qquad (2.23)$$

$$T(0, 1) = -(z_t)^1 \cdot \beta_t$$
, (2.24)

$$T(-1, 1) \implies (z_t)^2 \cdot \beta_t$$
 , (2.25)

where  $z_t \equiv \sqrt{-t/4m_c^2}$  and  $\beta_t \equiv 4G_t/(t-m_V^2) \sqrt{2}m_c$ .  $G_t$  contains the propagator of the exchanged sequential pole  $O_S$  and its coupled c-quark and q-quark virtual resonances so that

$$G_{t} \sim \frac{g_{c}}{t-m_{c\bar{c}}^{2}} \frac{f^{2}}{t-m_{O_{S}}^{2}} \frac{g_{q}}{t-m_{q\bar{q}}^{2}}$$
 (2.26)

Notice that the t-dependence at small t is dominated by the  $q\bar{q}$ -pole (say  $\epsilon$ ) and therefore the <u>t-dependence shows peripheral characteristics</u>. In the following, we do not need its specific form but keep in mind that it is c-mass dependent. There is little chance that this process will influence  $\psi$ -photoproduction at high energies since the cross section decreases like  $1/s^2$ ; at most it might be influential in the threshold region.

Within the framework of the sequential pole model one can think of a number of further possibilities. One might assume that two or more  $O_S$ -sequential poles are exchanged or that there is the combined exchange of  $O_V$ - and  $O_S$ -sequential poles as drawn in Fig. 6. This diagram gives the experimentally expected s<sup>1</sup> behavior; however it is twice suppressed since two sequential poles are exchanged.

We mention here a recent proposal that  $\psi$ -photoproduction might be damped by axial-vector exchange  $A_c$  which perhaps could be understood in this framework. Ioffe<sup>8</sup> argues that the Pomeron part of  $\psi$ -photoproduction should be strongly suppressed due to the vector mass dependence of the Pomeron residue like  $(1/m_V^2)$  leading to a suppression factor  $\gamma = (m_\rho^2/m_\psi^2)$  in the amplitude in going from  $\rho$ - to  $\psi$ -photoproduction. To explain the size of the  $\psi$ -photoproduction cross section Ioffe proposes that at  $E_{\gamma} \gtrsim 50$  GeV an 'elementary' axial vector meson might be exchanged with a relatively small coupling to  $\psi$  and nucleons; it should mainly consist of cc-quarks with a small admixture of q-quarks (but still considerably larger than in  $\psi$ ). Possible candidates are the  $P_c$  or  $\chi_c$  states around 3.5 GeV.

# 2.3 Phenomenological Pomeron

The schemes discussed so far are motivated by the field theoretic understanding of quark interaction through gluons (or gluon bound states). We now consider some phenomenologically motivated 'ad hoc' prescriptions for the Pomeron which were found to be quite useful in the description of diffractive phenomena. We assume that the interaction between q- and c-quarks at very high energies is mediated by the Pomeron whose coupling constant to the quarks is to be determined by experiment. We examine predictions of these models for the spin coupling of the Pomeron to the quarks.

In an earlier attempt Pumplin and Repko<sup>15</sup> have investigated the consequences of a model whose spin-couplings were assumed to be vector exchange between scalar quarks (Fig. 7b). Whilst we simply assumed an equipartitioning of the c-quark momenta, these authors close the cc-loop with a  $\gamma^{\mu}$ -coupling on the  $\psi$ -side. Formally this step corresponds to the annihilation of the c-quark pair and the creation of the  $\psi$ . The additional assumption that  $\psi$  is a nonrelativistic bound state of a pair of heavy constituents leads them to the equipartitioning of the momentum. After simplifying manipulations the model takes the form

$$T_{\gamma N \rightarrow VN} = is \cdot \sigma(VN) \cdot e^{\frac{\beta}{2}t} \frac{g_V}{m_V^2} \epsilon_V^{*\mu} \left\{ g_{\mu\nu} - \frac{k_\mu k'_\nu}{(k \cdot k')} \right\} \epsilon_{\gamma}^{\nu}$$

 $g_V \equiv e (m_V^2/2\gamma_V)$  is the vector dominance coupling constant and  $\sigma(VN)$  the total cross section for VN-scattering. In Section IV we discuss further characteristics of this model; here we present the form of the helicity amplitudes: Taking the asymptotic limit and dropping  $t \ll m_V^2$  in the kinematical factors we have:

$$T(1, 1) \stackrel{S \to \infty}{=} -K(t, m_V^2)$$
 , (2.28)

$$T(0, 1) \implies 2 \cdot \left(\frac{-t}{2m_V^2}\right)^{3/2} \cdot K(t, m_V^2) , \qquad (2.29)$$

$$T(-1, 1) = \left(\frac{-t}{m_V^2}\right) \cdot K(t, m_V^2)$$
, (2.30)

where

$$K(t, m_V^2) \equiv is \sigma(VN) e^{\frac{\beta}{2}t} \frac{g(m_V^2)}{m_V^2}$$
(2.31)

parametrizes the diffractive t-dependence and the (c-quark)-(q-quark) interaction which is hidden in  $\sigma(VN)$ . Note that the vector meson coupling constant is also mass-dependent. This model might seem artificial in that it describes the Pomeron spin couplings by vector exchange between spin-0 quarks which otherwise are treated as fermions. However the goal of constructing this model is different in that it emphasizes and extracts consequences of the bound state nature of  $\psi$ .

As an alternative to the model presented above one might try to describe the Pomeron spin couplings by a vector current as proposed by Feynman, Chou and Yang and others. <sup>16</sup> The elegance of this picture however suffers from intrinsic difficulties which can not be ignored when describing quark-quark interactions. Any  $\gamma^{\mu}$ -coupling for the Pomeron forces it to be a C=-1 object instead of C=+1, only axial vector couplings have C=+1. Consequently any model of this type will lead either to a vanishing amplitude by Furry's theorem<sup>17</sup> if a  $\gamma^{\mu}$ coupling is assumed for the transition  $c\bar{c} \rightarrow \psi$  or force the created vector meson to have C=+1.

In this last phenomenological model we shall consider, we leave the constituent picture of the vector mesons  $\rho$ ,  $\omega$ ,  $\phi$ ...  $\psi$ ... and assume that VMD holds instead. We view vector meson photoproduction as represented in Fig. 8.

In a recent paper Collins and Gault<sup>16</sup> used the method of covariant Reggeization in order to determine the spin structure of the helicity amplitudes. Without going into the details of this approach we simply state the form of the amplitude for  $\gamma N \rightarrow VN$ ; the nucleons are treated as scalars for simplicity

$$T(\lambda_{V},\lambda_{\gamma}) = \frac{\xi_{\pm}}{\alpha_{P}^{2}} (P \cdot Q)^{\alpha} P \cdot V(\lambda_{V},\lambda_{\gamma}) \quad .$$
 (2.32)

Here  $\xi_{\pm}$  is the usual signature factor,  $\alpha_{p} = \alpha_{p}$  () represents the Pomeron trajectory and the product P·Q expressed in terms of the invariants reads:

$$P \cdot Q = \frac{1}{2} \left\{ s + \frac{t - 2m_N^2 - m_V^2}{2} \right\}$$
 (2.33)

The explicit forms for the  $\gamma \rightarrow V$  transition vertex are:

$$V(1, 1) = \left[-\frac{t}{2}g_1 - g_2\right] ,$$
 (2.34)

$$V(0, 1) = \sqrt{\frac{-t}{2m_V^2}} \left[ -\left(\frac{t+m_V^2}{8}\right)' g_1 + g_2 + \frac{1}{2}g_3 \right] , \qquad (2.35)$$

$$V(-1, 1) = t \cdot \frac{g_1}{2}$$
, (2.36)

where  $g_1, g_2, g_3$  are constants. The fact that this model has enough freedom to adjust for SCH-violation or SCHC (according to the choice of its parameters) leads us to include it in our investigation. Furthermore one notices that P·Q is the relevant Regge variable rather than s.

### **III.** SPIN DEPENDENCE

In the preceding section we have presented the models to be investigated. In this section we discuss their spin characteristics, which can be determined by measuring the decay angular distribution of the lepton-pair<sup>18, 19</sup>

$$\begin{split} & \mathbb{W} \left( \boldsymbol{\theta}, \boldsymbol{\phi} \right) = \frac{1}{2} \left( \boldsymbol{\rho}_{11} + \boldsymbol{\rho}_{-1-1} \right) \left( 1 + \cos^2 \boldsymbol{\theta} \right) + \boldsymbol{\rho}_{00} \cdot \sin^2 \boldsymbol{\theta} \\ & \quad + \frac{1}{\sqrt{2}} \left[ \operatorname{Re} \boldsymbol{\rho}_{10} - \operatorname{Re} \boldsymbol{\rho}_{-10} \right] \cdot \sin 2\boldsymbol{\theta} \cdot \cos \boldsymbol{\phi} \\ & \quad - \frac{1}{\sqrt{2}} \left[ \operatorname{Im} \boldsymbol{\rho}_{10} + \operatorname{Im} \boldsymbol{\rho}_{-10} \right] \cdot \sin 2\boldsymbol{\theta} \cdot \sin \boldsymbol{\phi} \\ & \quad + \operatorname{Re} \boldsymbol{\rho}_{1-1} \sin^2 \boldsymbol{\theta} \cdot \cos 2\boldsymbol{\phi} - \operatorname{Im} \boldsymbol{\rho}_{1-1} \sin^2 \boldsymbol{\theta} \cdot \sin 2\boldsymbol{\phi} \,. \end{split}$$
(3.1)

The spin dependence of  $\psi$ -photoproduction is contained in the density matrix  $\rho_{VV}$ , and it is this quantity we are mostly concerned with in the following discussion. We closely follow the presentation in Section II.

### 3.1 Phenomenological Models

We start our discussion with the phenomenological models, which we regard as tools to study the influence of the vector meson mass on SCHC at asymptotic and nonasymptotic energies.

The DH-model was constructed such that gauge invariance holds, easy extrapolation to  $\gamma N \rightarrow \pi^+ \pi^- + N$  is possible and asymptotically <u>exact</u> SCHC holds. By extrapolating in the vector meson mass, we have applied this model to  $\psi$ photoproduction.

The helicity amplitudes given in Eqs. (2.1) - (2.3) show that the flip amplitudes grow with one less power in s and therefore the density matrix element  $\rho_{00}^0 \sim \frac{1}{s^2}$  approaches zero very rapidly with increasing energy. Taking a moderate fixed s-value, say 30 GeV<sup>2</sup>, and increasing m<sub>V</sub> enhances the flip amplitudes, causing  $\rho_{00}^0$  to increase. For a limited t-range and large s we can use the rule

$$\rho_{00}^{0} \sim \frac{|\mathbf{t}| \cdot \mathbf{m}_{V}^{2}}{s^{2}} \quad .$$
(3.2)

The helicity amplitudes in Eqs. (2.1) - (2.3) are for asymptotic s-values. We have numerically determined the amplitudes and  $\rho_{00}^0$  for nonasymptotic energies keeping all spin factors in the invariant expansion exact. For instance, applying this model at s = 20 GeV<sup>2</sup> means extrapolating the asymptotic form of the model down into the threshold region. We have intentionally done this exercise in order to study the influence of the kinematical terms due to spin. Our results are presented in Fig. 9. For  $\psi$ -photoproduction (solid line) one notices a strong effect in  $\rho_{00}^0$  at t= -2.0 GeV<sup>2</sup>. The onset of the curve at t=-0.5 GeV<sup>2</sup> reflects the  $|t_{min}|$ -limit due to kinematics. In comparison the same calculation for  $\rho$ -photoproduction (dashed line), which of course is not in the threshold region, shows an unmeasurably small violation of SCHC.

The MW-model emphasizes the correct analyticity structure of the scattering amplitude and the connection between the deep-inelastic and the (quasi) elastic regions. This model does satisfy the gauge constraint; however, asymptotic SCHC is not imposed. The asymptotic form of the helicity amplitudes Eqs. (2.5) - (2.7) shows that flip as well as nonflip amplitudes grow equally in s; therefore one would not expect SCHC to be true in this model. However, as we shall see, this feature is well satisfied. Equations (2.5) - (2.7)also exhibit the vector mass dependence. The nonflip amplitude decreases like  $(1/m_V)$  whereas the flip amplitudes each decrease with one additional power in  $m_V$ . The parameter a is the threshold mass on the photon side and we assume it to be constant. We conclude that increasing the vector meson mass at asymptotic energies damps the flip amplitudes relative to the nonflip one and therefore SCHC will improve. To determine the influence of the spin factor at nonasymptotic energies we have numerically evaluated this model keeping all kinematical factors exact. This corresponds to extrapolating its asymptotic form down to the threshold region in the case of  $\psi$ -photoproduction. In Fig. 10 we present our numerical results. At s = 20 GeV<sup>2</sup> the density matrix element  $\rho_{00}^{0}$  of  $\psi$ -photoproduction rises almost linearly and exhibits a substantial violation of SCHC at t = -2.0 GeV<sup>2</sup>; however, for large s-values  $\rho_{00}^{0}$  falls below measurable limits (s = 200 GeV<sup>2</sup>). It is interesting to notice that the production of the lighter vector mesons leads to a bigger SCH-violation at high energies. In fact, changing the energy from s = 20 GeV<sup>2</sup> to 200 GeV<sup>2</sup> for  $\rho$ -photoproduction leads to a small effect since 20 GeV<sup>2</sup> is almost asymptotic for  $m_{\rho}^{2}$  = 0.58 GeV<sup>2</sup> whereas for  $m_{p}^{2} \simeq 10 \text{ GeV}^{2}$  this is not the case.

While carrying out the numerical analysis of this model, we discovered a computing error in the  $\rho$ -photoproduction density matrix elements given in Ref. 10. Therefore, in Fig. 11 we show the corrected results along with the data. The density matrix elements are seen to be in reasonably good agreement with experiment.

In concluding our discussion of the model, we again emphasize that, because of the use of the generalized Callan-Gross relation, the density matrix elements in this model are independent of the invariant amplitudes, so that the spin structure of the model is apparently independent of the dynamics. Of course, the dynamics is hidden in the use of Eq. (2.4). Furthermore, we stress that Eq. (2.4) is instrumental in providing approximate SCHC because it relates  $T_1$  and  $T_2$  in such a way that the amplitude A is small.<sup>9</sup> This statement is rather model independent since the density matrix elements are independent of the form of  $T_1$  and  $T_2$ . The phenomenological models test specific parametrizations of the amplitudes and thus emphasize global features. The constituent models, which we will now investigate, involve assumptions about the binding forces of the confined quark system as well as model assumptions about its interaction with the nucleon. Here we will maintain the assumptions of Section II and concentrate on the interaction between the c-quarks and the q-quarks.

# 3.2 Gluon Exchange Models

We assume that gluons are exchanged between the c-quarks and the conventional q-quarks in the nucleon. The model we consider here has been defined in Section II. We first discuss the exchange of scalar gluons (which might seem to be of academic interest but will be of later use) and subsequently present our results about the same model with vector gluons as mediators.

Let us start with 'scalar gluon exchange'. The asymptotic form of the helicity amplitudes for diagrams Fig. 4(a-f) are given in Eqs. (2.14) - (2.16). For asymptotic energies one notices that

- 1) The nonflip amplitude of  $T_{abcd}$ , which dominates the asymptotic behavior, is essentially s-independent whereas the nonflip amplitude of  $T_{ef}$  decreases like ~1/s<sup>2</sup> and therefore diagrams (e) and (f) may be neglected as  $s \rightarrow \infty$  in comparison to diagrams (a-d).
- 2) T<sub>abcd</sub> is real at asymptotic energies as it must be according to spin-0 exchange.
- 3) There is moderate t-dependence in the nonflip amplitude of  $T_{abcd}$  due to the function  $F_1$  and the propagator.
- 4) The flip amplitudes of T<sub>abcd</sub> and T<sub>ef</sub> each decrease with an additional power in s, which means that the <u>exchange of two scalar</u> gluons leads to SCHC at asymptotic s-values.

All the above results hold for asymptotic energies. However, it is interesting to investigate the influence of a large vector meson mass on the spin characteristics of this model at nonasymptotic energies. Therefore, we have performed a numerical study of the helicity amplitudes and the density matrix elements, which is exact in the kinematical factors due to spin, and to leading order in the invariant integrals. In extrapolating this model down to lower energies, we are aware that this procedure can not reproduce correctly the threshold rise, but we believe that the spin structure is correctly reproduced.

Taking  $m_{G}^{=1}$  GeV, in Fig. 12 we show  $\rho_{00}^{0}$  for  $\psi$  (solid line) and  $\rho$  (dashed line) photoproduction at s=30 GeV<sup>2</sup>.  $\psi$ -photoproduction exhibits considerable SCHC violation at larger t-values, while  $\rho$ -photoproduction is essentially helicity conserving. We interpret this as due to the fact that s=30 GeV<sup>2</sup> is fairly near threshold for  $\psi$ -photoproduction, whereas for  $\rho$ -photoproduction all (mass)<sup>2</sup> are negligible compared to s. In Fig. 12 we also show, for comparison,  $\rho_{00}^{0}$  for  $\psi$ -photoproduction at s=20 GeV<sup>2</sup> although high energy approximation of the invariant amplitudes  $W_i$  becomes questionable in this region. Clearly, SCHC violation becomes more marked as threshold is approached.

In Fig. 13 we study the gluon mass dependence of  $\rho_{00}^0$  for  $\psi$ -photoproduction at fixed s = 20 GeV<sup>2</sup>. We show results for gluon masses of 0.2 GeV and 5 GeV (dash-dotted lines) which may be compared with the curve for m<sub>G</sub>=1 GeV (solid line). In general, <u>increasing the gluon mass decreases SCHC violation</u>. This fact is further illustrated in Fig. 14 where we plot the m<sub>G</sub>-dependence of  $\rho_{00}^0$ for  $\psi$ - and  $\rho$ -photoproduction at s = 30 GeV<sup>2</sup> and t = -0.5 GeV<sup>2</sup>. Notice that the results are quite sensitive to the choice of the gluon mass, so that to make definite predictions based on this model, one would require a fairly accurate estimate of m<sub>G</sub>. Diagrams (e) and (f) for two scalar gluon exchange compete with diagrams (a-d) only in the amplitudes T(0, 1) and T(-1, 1). Their contribution to SCHC violation is indicated by a comparison of the solid and dashed lines in Fig. 13. Both curves are for  $\psi$ -photoproduction at  $s = 20 \text{ GeV}^2$ , but the latter does not include the contribution from diagrams (e) and (f). Evidently <u>these diagrams</u> interfere constructively with diagrams (a-d) in the amplitude T(0, 1) and so contribute to SCHC violation. We also note here that asymptotically Re T(1, 1) dominates Im T(1, 1). At  $s = 30 \text{ GeV}^2$  we find that this is true for  $\rho$ -photoproduction, reflecting the proximity of the threshold.

As the energy is increased, the SCHC limit is rapidly approached. For example at  $s = 200 \text{ GeV}^2$ ,  $\rho_{00}^0 \leq 0.01$  for  $\psi$ -photoproduction and helicity is even better conserved for the  $\rho$ . Of course this is expected since  $\rho_{00}^0 \propto s^{-2}$  at high s.

To summarize, exchange of two scalar gluons leads to asymptotic SCHC, but nonnegligible violation of SCHC at nonasymptotic energies. The result depends fairly sensitively on the gluon mass, but for  $m_G^{=1}$  GeV the helicityflip predicted by the model should be measurable at SLAC energies.

We now extend our analysis to the model defined by the Feynman diagrams in Fig. 4 with two vector-gluons exchanged.

As in the case of two scalar-gluon exchange, two vector-gluon exchange conserves helicity at high energies. Again we wish to investigate whether this property holds at low energies. Our analysis here differs from that of the scalar gluon case in that the kinematical factors are taken to leading or first nonleading order in s. This introduces some error into the result; for instance the flip amplitude vanishes at t=0 rather than at  $t_{min}$  in this approximation. For this reason, we restrict our numerical analysis to  $s \ge 30$  GeV<sup>2</sup> for

 $\psi$ -photoproduction, where we have some confidence in the precision of the results. Again, we treat the invariant integrals to leading order in s.

The amplitudes  $T_{ef}$  compete with  $T_{abcd}$  asymptotically, for all three helicity amplitudes. That is both sets of diagrams give

$$T(1, 1) \propto s$$
,  
 $T(0, 1) \propto const$ , (3.3)  
 $T(-1, 1) \propto const$ .

The approximations we use in the expansion of the kinematical factors are as follows: For the nonflip amplitude T(1, 1) we compute both the leading and first nonleading contribution in the sum  $T_{abcd}$ . For simplicity  $T_{ef}$  is restricted to the leading contribution. In practice, we find that the first nonleading contribution to  $T_{abcd}$  is small compared to the leading contribution at  $s = 30 \text{ GeV}^2$ , so that the error involved in dropping the first nonleading contribution in  $T_{ef}$  is probably small. The flip-amplitudes T(0, 1) and T(-1, 1) are computed to leading order in s for both  $T_{abcd}$  and  $T_{ef}$ .

Using these approximations and taking  $s = 30 \text{ GeV}^2$  and  $m_G = 1 \text{ GeV}$ , we plot  $\rho_{00}^0$  for  $\psi$ -photoproduction (solid line) and  $\rho$ -photoproduction (dashed line) in Fig. 15. The outstanding feature of these results is that <u>SCHC is almost</u> <u>perfectly satisfied</u>. This is to be contrasted with the two scalar gluon exchange case (Fig. 12) where SCHC is violated at lower energies.

Taking  $m_{G} = 0.2 \text{ GeV}$  (dashed-dotted line) significantly changes  $\rho_{00}^{0}$  for  $\psi$ photoproduction, although observation of this effect would be extremely difficult. Whilst carrying out this analysis of the  $m_{G}$ -dependence of  $\rho_{00}^{0}$  we noticed that the amplitude Im T(1, 1) has a zero at a particular gluon mass around  $m_{G}$  0.2-0.5 GeV which manifests itself by a significant peak in  $\rho_{00}^{0}$ . The vanishing of Im T(1, 1) and change of its sign is due to a cancellation of the amplitudes T<sub>abcd</sub> and  $T_{ef}$ . Note that, since  $\psi$ -photoproduction is not an elastic process, the indefinite sign of Im T(1, 1) does not imply a violation of unitarity. In the limit  $m_{G} \rightarrow 0$ all amplitudes  $T_{a-f}$  diverge logarithmically since the t-dependent functions diverge<sup>19</sup>

$$f_{t} \approx \frac{m_{G} \rightarrow 0}{-t} \frac{2}{-t} \ln(m_{G}^{2}) \qquad \text{for } T_{a,b,c,d} \qquad (3.4)$$

and

$$h_{t} \approx \frac{m_{G} \rightarrow 0}{-t} \frac{2}{\left(\frac{t}{4} - m_{c}^{2}\right)} \ln\left(m_{G}^{2}\right) \quad \text{for } T_{e,f} \quad . \tag{3.5}$$

It is easy to show that the contributions of these terms to the nonflip amplitude cancel (apart from the finite terms) in the limit  $m_{G} \rightarrow 0$ , so that there is no  $\ln m_{G}^{2}$  -type divergence in the overall amplitude.

This feature is not surprising since we are producing a color neutral system ( $\psi$ ) which can not radiate gluons. The infrared divergent terms can not be cancelled by soft gluon terms<sup>20</sup> and therefore the divergences have to cancel themselves in the set of diagrams given in Fig. 4.

In conclusion, we again remark that, in general, <u>two vector gluon exchange</u> <u>leads to a very small violation of SCHC in photoproduction of vector mesons</u>, <u>even near threshold</u>. Perhaps this result might have been anticipated, since a  $\gamma^{\mu}$ -type coupling is known to conserve helicity at both high and low energy.<sup>21</sup>

# 3.3 Sequential Pole Model

The advantage of the sequential pole model lies in its power of predicting and connecting OZI-rule violating interactions. We have investigated its consequences in a spin analysis of  $\psi$ -photoproduction. In Eqs. (2.23)-(2.25) we have determined the helicity amplitudes for O<sub>S</sub>-exchange and find a strong violation of SCHC at asymptotic energies, which is characteristic of any spin-0 exchange. It is doubtful whether  $O_S$ -exchange is influential since spin-0 exchange leads asymptotically to:  $T \xrightarrow{S \to \infty} s^0$ . Therefore <u>if this mechanism is</u> <u>operative at all, it should be mostly felt in the threshold region and manifest</u> <u>itself by a strong violation of SCHC</u>. Double exchange of  $O_S$  is twice suppressed and even less influential. Interpreting our calculations of two scalar-gluon exchange in this sense of double  $O_S$ -exchange we conclude that there is substantial violation of SCHC at nonasymptotic energies; however, SCHC holds as  $s \to \infty$ .

In our discussion in subsection II. 2. 2 we also suggested the combined exchange of  $(O_V + O_S)$  as drawn in Fig. 6 which would give the correct asymptotic s-dependence. Although twice suppressed, we expect this process to be of the same order of magnitude as single  $O_S$ -exchange in the threshold region. From our earlier experience with vector and scalar exchanges, we expect such a process to violate SCHC as  $s \rightarrow \infty$ . If Ioffe's suggestion of an axial-vector meson  $A_c$ , mediating c-quarks and q-quarks is correct, again it should lead to a strong violation of SCHC. His arguments rely essentially on an estimate which appears to be too stringent.<sup>22</sup>

In summarizing we state that <u>sequential poles give a peripheral-like t-</u> dependence and manifest themselves by violation of <u>SCHC</u>.

# 3.4 Phenomenological Pomeron

The fact that the produced vector mesons in  $\gamma N \rightarrow VN$  are bound states of quark-pairs with charge conjugation C=-1, considerably constrains the possibilities of constructing simple spin couplings of a C=+1 Pomeron to the quarks.

The  $\gamma^{\mu}$ -coupling, as if the <u>Pomeron has photon-like spin characteristics</u>, <u>must be rejected</u> since it enforces charge conjugation C=-1; this feature is intrinsic to the vector Lagrangian  $\mathscr{L}_{I} = A_{\mu} j^{\mu}$ . The model investigated by Pumplin and Repko<sup>15</sup> treats the quarks as spin zero objects in their interaction with the Pomeron, which is unsatisfactory.

Nevertheless, we consider it worthwhile to examine the consequences of spin zero exchange as exemplified in this model. Equations (2.28) - (2.30) clearly indicate that substantial violation of SCHC is expected. This is illustrated in Fig. 16 where  $\rho_{00}^0$  is plotted for  $\psi$  (solid line) and  $\rho$  (dashed line) photoproduction. For smaller vector meson masses SCHC violation appears at smaller t-values whereas for large  $m_V^2$  violation of SCHC is less likely to be discovered due to the exponential t-dependence. Note that increasing the energy does not significantly reduce violation of SCHC as it does not hold asymptotically in a model with spin 0 exchange.

So far we have assumed that the Pomeron interacts with only one quark at a time in the vector meson. One might depart from such premises and assume that the Pomeron interacts with the constituent bound state as an entire system.

Application of covariant Reggeization then defines the spin couplings. Equations (2.34) – (2.36) tell us that both SCH-violation or SCHC is possible according to the choice of the parameters. Since such models should apply best for the lower mass vector mesons where the quark bindings are strong, SCHC forces  $g_1$  and  $g_2 + \frac{1}{2}g_3$  to be small. Keeping only  $g_1$  small does lead to a substantial violation of SCHC which fades away as the vector meson mass increases. The increase of the vector meson mass therefore damps the density matrix element  $\rho_{00}^0 \sim (1/m_V^2)$ . On the other hand keeping  $g_2$ ,  $g_3$  small predicts a moderate  $\rho_{00}^0$  which increases with  $m_V^2$  whereas the density matrix element  $\rho_{1-1}^0 \cong \frac{1}{2}$ .

### VI. MASS DEPENDENCE

A distinctive characteristic of  $\psi$ -photoproduction in comparison to photoproduction of the lighter vector mesons is the large mass difference:  $m_{\psi}^2 \sim 10 \cdot m_{\rho}^2$ . In this section we shall assume that all vector mesons are produced by the same mechanism and study the influence of the vector meson mass. Our investigation is motivated by the observation that the size of the amplitudes of some of the models presented in Section II are dependent on the vector meson mass.

In performing this analysis we keep in mind that the amplitude of  $\psi$ photoproduction is suppressed in comparison to  $\rho$  photoproduction and that the suppression might be due to the difference in mass.

### 4.1 Phenomenological Models

The two phenomenological models introduced in subsections II. 1.3 and II. 1.4 have substantially different dependences on the vector meson mass and in turn different suppression mechanisms. The leading amplitude of the DHmodel is essentially independent of  $m_V$  although the function  $\beta_t$  might depend on  $m_V$ ; it parametrizes the Pomeron residue functions which may strongly depend on the vector meson mass depending on model assumptions. If  $m_V^2$  increases, a mass dependence like  $1/m_V^2$  as suggested by Regge theory is quite possible and would predict a suppression factor  $(m_\rho^2/m_\psi^2) \cong \frac{1}{16}$  whilst extrapolating these amplitudes from  $\rho$  to  $\psi$ .

Suppression of the MW-amplitudes is more explicit. For  $\alpha_{\rm P}\sim\!\!1$  we encounter a suppression factor

$$\frac{m_{\rho} \cdot g_{\rho}}{m_{\psi} \cdot g_{\psi}} \sim \frac{1}{32} \tag{4.1}$$

which is slightly too strong. Suppression here is due to the particular choice of the scaling variable  $\omega$  as determined in Eq. (2.5) and the inverse of the VMD-coupling constant.

In the following we discuss the  $m_c$ -dependence of the models which assume that the vector mesons are composed of c-quarks. Neglecting binding effects, we considered in Section II the production of a free fermion pair (which the nucleons treated as scalars throughout). The  $m_c$ -dependence of this amplitude is misleading since the dimension of the Lorentz invariant T-matrix defined as

$$S = 1 + i(2\pi)^{4} \delta^{4}(p_{i} - p_{f}) \cdot \frac{T_{fi}}{N}$$
(4.2)

is:  $[T] = [1/M^2]$  whereas for vector meson production it is [1]. N is a product of normalization factors for fermions and bosons. In the following we therefore take bound state effects into account and treat the final state  $c\bar{c}$ -bound state as a vector particle.

### 4.2 Sequential Pole Model

For pedagogical reasons we do not follow the presentation of Section II but begin with the sequential pole model which assumes single  $O_S$ -exchange. We first assume that there is no binding between the cc-pair and take bound state effects into account afterwards.

Ignoring the influence of  $G_t(m_c^2)$ , the leading amplitude T(1, 1) Eq. (2.23) of this model decreases like  $(1/m_c)$  in the forward direction. The exchange of a cc-resonance further damps the amplitude through  $G_t$ . As  $m_c$  increases, the dominating amplitude therefore decreases like

$$T \sim \left(1/m_c^3\right) \tag{4.3}$$

in the region where t is small.

We now ask whether bound state effects will modify this result. The bound state nature of  $\psi$  has been investigated by Pumplin and Repko<sup>15</sup> with different intentions. We sketch some of the arguments. In order to describe photoproduction of a heavy constituent pair which subsequently is bound by a confining potential in a vector state V, we consider the three processes drawn in Fig. 7. The first one (a) serves to define the  $\gamma$ -V coupling constant, whereas the third one (c) fixes the normalization of the cc-V transition amplitude; Fig. 7(b) represents photoproduction of V.

In order to simplify the spin part of the amplitudes we assume a  $\gamma^{\mu}$ coupling for the cc-V transition and consequently treat the vector-meson as an 'elementary' spin-1 particle. Figure 7(a) specifies the connection between the bound state wave function of the cc-system and the VMD-constant  $g_V \equiv em_V^2/2\gamma_V$  which reads:

$$g_{V} \equiv g(m_{c}^{2}) = (2e_{\lambda} \cdot m_{V}) \cdot \int \frac{d^{3}q}{(2\pi)^{3}} \eta \phi(q)$$
$$= \frac{1}{\sqrt{8}} e_{\lambda} \cdot m_{V} \cdot R(0) \cdot \eta \quad . \tag{4.4}$$

 $e_{\lambda} \equiv \lambda \cdot e$  is the c-quark charge. The normalization factor is fixed by the requirement that the form factor in VN  $\rightarrow$  VN scattering (Fig. 7(c)) reduces to 1 in the forward direction. The mass dependence of R(0), the radial wave function at the origin, is unknown; it is adjusted according to the experimental values of the VMD-coupling constant.

The analogous steps can be carried out for vector meson photoproduction as viewed in Fig. 7(b). The dominant contribution to the integral comes from the region where  $q \sim \frac{1}{2}k'$ ; the trace may be evaluated and the pole in  $q_2^2$  separated from the integral. After simplifying manipulations the amplitude reads:

$$T = \frac{g(m_V^2)}{m_V} G_t(m_c^2) \epsilon_{\mu}^* \left(g^{\mu\nu} - \frac{k^{\mu}k'^{\nu}}{(k \cdot k')}\right) \epsilon_{\nu} , \qquad (4.5)$$

where  $g(m_c^2)$  is defined in Eq. (4.4). Paying particular attention to the  $m_V^$ dependence we notice that the trace introduces the factor  $m_V(k \cdot k')$  which cancels the pole in  $q_2^2$ . In comparison to Eq. (4.3) this result reflects the fact mentioned earlier that the amplitude for vector meson production and the production of a free fermion pair differ in their dimensions by  $[M^2]$ . The  $m_V^-$ dependence depends substantially on  $g(m_V^2)$ . The authors of Ref. 15 use  $g(m_V^2) = 0.13 \cdot e_{\lambda} \cdot m_V^2$ . (4.6)

This formula was adjusted for  $\psi$  (by the choice of R(0)) and predicts within a factor of 2 the correct lower mass VMD-coupling constants.

From the above we conclude that the amplitude of the sequential pole model behaves like

$$T \sim \left(\frac{1}{m_V}\right)$$
 (4.7)

if the vector meson mass is varied.

### 4.3 Gluon Exchange Model

Discussion of the constituent model with vector-gluons needs consideration of diagrams (a-d) and (e-f) in Fig. 4. Supposing that there is no interaction between the final state c-quark pair, the dominating contribution of the amplitudes as given in Eqs. (2.17) - (2.18) might lead one to the incorrect conclusion that there is strong damping of the amplitude  $T_{abcd}$  as we extrapolate to larger  $m_V$ -values. The function<sup>19</sup>  $f_t$  in this same amplitude is  $m_V$ -independent whereas  $h_t$  appearing in  $T_{ef}$  decreases with increasing vector meson mass; this is a reflection of the fact that the amplitude  $T_{ef}$  hides the pole at  $t = m_V$ , which, as was shown in Section III, appears explicitly in the limit  $m_G \rightarrow 0$ .

Going through the same steps sketched in the preceeding subsection, we find

$$\Gamma_{abcd} \propto G \cdot \frac{g(m_V^2)}{m_V^2} 2 \sqrt{2} \cdot f_t \cdot s , \qquad (4.8)$$

$$T_{ef} \propto -\sqrt{2} G g(m_V^2) \cdot h_t \cdot s$$
 , (4.9)

which makes it obvious that for asymptotic energies little variation may be expected as we extrapolate in the c-quark mass. Without going into the details we mention that the exchange of two scalar gluons reveals the same characteristics.

# 4.4 Phenomenological Pomeron

The amplitude of the PR-model,<sup>25</sup> given in Eq. (2.14) shows that there is no explicit  $m_V$ -dependence once one accepts that  $g(m_c^2) \propto m_V^2$ . However  $m_V$ dependence might be hidden in the elastic (c-quark)-nucleon cross section. We point to the fact that the c-quark, interacting with the nucleon, is far off-mass shell since its actual mass is  $Q_t^2 \equiv \left(k - \frac{1}{2}k^{\dagger}\right)^2 = \frac{1}{2} \cdot t - m_c^2$ . If a Pomeron is exchanged one is faced with the question whether the residue function  $\beta_t Q_t^2$ depends strongly on the off-shell mass of the c-quark. Replacing in Fig. 7(b) the photon by the vector meson  $V(c\bar{c})$  results in  $Q_t^2 \equiv \left(k - \frac{1}{2}k^{\dagger}\right)^2 = \frac{t}{2} + \left(m_V^2/4\right)$ ; in the forward direction the c-quark here is on its mass shell. We conclude that in this model any c-quark mass dependence as well as suppression must be blamed on the (c-quark)-nucleon interaction instead of  $g(m_V^2)$ .

The amplitudes of the model constructed by use of covariant Reggeization are proportional to  $(P \cdot Q)^{\alpha}P$  (see Eq. (2.32)). Due to Eq. (2.33) there is slight

suppression as we go to higher vector meson masses at fixed s. Again the mass-dependence of the VMD-coupling constant is important.

# V. CONCLUSION

In this paper we have presented a systematic study of the spin and mass dependence of models for  $\psi$ -photoproduction. Our main interest has centered on the influence of the large c-quark mass in spin measurements and on the size of the scattering amplitude.

These questions have been pursued in the context of several models for vector meson photoproduction in order to keep our conclusions as general as possible. Two of the models are phenomenological and the others assume the creation of a c-quark pair which subsequently transforms into the vector meson bound state. The c-quark nucleon interaction is mediated by gluons, sequential poles or a phenomenological Pomeron.

The spin characteristics of the phenomenological models are hidden in the kinematical terms of the invariant expansion, whereas in constituent models the spin of the "object" mediating between the c-quarks and the nucleon is tested. At asymptotic energies, all models except single scalar gluon exchange predict that SCHC violation becomes immeasurably small. Since scalar gluon exchange is not expected to dominate asymptotically, it would probably not be fruitful to search for spin-dependent effects at FNAL energies. On the other hand, we have found that in several models, substantial violation of SCHC may be expected at SLAC energies. These effects should be measurable for  $-t \approx 1 (\text{GeV/c})^2$ , and are due to the proximity of threshold.

The single, striking exception to this rule is two vector gluon exchange, for which SCHC is almost exactly conserved at all energies. This fact is particularly significant in that the charmonium picture for the  $\psi$  combined with

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two vector gluon exchange is perhaps the most attractive model for  $\psi$  photoproduction we have investigated. If experiments on the spin dependence of  $\psi$  photoproduction reveal that  $\rho_{00}^0$  is very small, this would provide strong evidence in favor of two vector gluon exchange. If, on the other hand,  $\rho_{00}^0 \gtrsim 0.1$  at SLAC energies, then measurements of the size and energy dependence of SCHC violation could, in principle, distinguish between the various models we have studied. The phenomenological models generally provide moderate SCHC violation (Figs. 9, 10), whereas scalar gluon exchange models exhibit quite dramatic SCHC violation (Figs. 12, 13, 16). As an example of the different energy dependence of the models, SCHC is approached much more rapidly in the DH model than in the MW model as the energy increases.

We have taken the point of view that  $\rho\omega\phi$  and  $\psi, \psi'\ldots$  are all produced by the same mechanism and investigated the consequences of mass extrapolation. The phenomenological models can account for the suppression of the amplitude in going from  $\rho$  to  $\psi$ , whereas the constituent models suffer from the uncertainty of the m<sub>c</sub>-dependence of the VMD coupling constant (and in turn of the bound state wave function at the origin). If  $g_V \propto m_c^2$ ,  $\psi$ -photoproduction is not suppressed relative to  $\rho$ -photoproduction in these models.

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- 25. Henceforth 'PR-model' stands for the model by Pumplin and Repko, see Ref. 15.

### FIGURE CAPTIONS

- 1. Zweig rule violating decays as viewed in the sequential pole model.
- 2.  $\psi$ -photoproduction in a picture of quarks interacting via gluons.
- 3. Quark interaction in the Low-Nussinov model.
- 4. Photoproduction of  $\psi \equiv (c\bar{c})$  as viewed in a two-gluon exchange model.
- 5. Photoproduction of  $\psi \equiv (c\bar{c})$  as viewed in the sequential pole model with scalar O<sub>S</sub>-exchange.
- 6. Photoproduction of  $\psi \equiv (c\bar{c})$  as viewed in the sequential pole model with simultaneous scalar and vector exchange  $(O_S + O_V)$ .
- 7. (a) Diagram used to determine the vector meson dominance coupling constant  $g(m_V^2)$ . (b) Photoproduction of  $\psi$  via spin-o exchange taking bound state effects into account. (c) Elastic  $\psi$ N-scattering.
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- 9. DH-model prediction for the t-dependence of the density matrix element  $\rho_{00}^0$  for  $\rho$  and  $\psi$ -photoproduction at  $s = 20 \text{ GeV}^2$ .
- 10. MW-model prediction of the t-dependence of the density matrix element  $\rho_{00}^0$  for  $\rho$  and  $\psi$ -photoproduction at s = 20 GeV<sup>2</sup> and 200 GeV<sup>2</sup>.
- 11. (a-c) MW-model prediction for  $\rho$ -photoproduction. The corrected  $\rho^{0}$  spin density matrix elements are plotted versus -t (see Ref. 10 and text). The data are taken from Ref. 3.
- 12. Two-gluon exchange model with <u>scalar</u> gluons. t-dependence of the density matrix element  $\rho_{00}^0$  for  $\rho$  and  $\psi$ -photoproduction at  $s = 20 \text{ GeV}^2$  and  $s = 30 \text{ GeV}^2$ .
- 13. Two-gluon exchange model with <u>scalar</u> gluons. t-dependence of the density matrix element  $\rho_{00}^0$  as a function of the gluon mass; the dash-dotted

curves represent contributions from all diagrams. The influence of diagrams (e) and (f) is shown by the dashed and solid lines; the former represents contributions from diagrams (a-d) only whereas the latter represents contributions from all diagrams (a-f).

- 14. Two-gluon exchange model with scalar gluons. Influence of the gluon mass on the size of  $\rho_{00}^0$  for  $\rho$  and  $\psi$ -photoproduction. The kinematical parameters are fixed at s = 30 GeV<sup>2</sup> and t = -0.5 (GeV/c)<sup>2</sup>.
- 15. Two-gluon exchange model with vector gluons. t-dependence of  $\rho_{00}^0$  for  $\rho$  and  $\psi$ -photoproduction with different gluon masses;  $s = 30 \text{ GeV}^2$ .
- 16. Pumplin-Repko-model prediction for the density matrix element  $\rho_{00}^0$  for  $\rho$  and  $\psi$ -photoproduction at  $s = 20 \text{ GeV}^2$  and 200 GeV<sup>2</sup>.







Fig. 2



Fig. 3



(b)

















Fig. 6







Fig. 7



Fig. 8



Fig. 9



Fig. 10



Fig. 11



14.1

Fig. 12



Fig. 13



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Fig. 14



Fig. 15



Fig. 16