Photoproduction of J (ψ) particles and rising photon-nucleon cross sections*

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The existence of vector mesons with masses above 3 GeV suggests study of their contributions to the Compton sum rule. The Compton sum rule is used to place upper limits on photoproduction cross sections for such recently discovered and yet to be found $J^P = 1^-$ particles. We are led to the result that the total proton photoabsorption cross section and forward Compton-scattering cross section will rise in the range of energies (above ~ 50 GeV) available for photon experiments at the Fermilab accelerator. Discussion is given on the implications of such a rising photon-proton cross section for vector-meson dominance (VMD), the quark model, generalized VMD, and the new duality, and for scaling breaking.

I. INTRODUCTION

The discovery of the $J(\psi)(3.1)$ particle[1] led to considerable theoretical activity seeking an explanation for its unusual properties and for those of the heavier ψ's.[2] Particularly, the J (ψ) and $\psi'(3.7)$ were found to have extremely narrow widths but their couplings to charged lepton pairs are comparable to those of the lower-mass well-known vector mesons. A natural resurgence of older[3] SU(4) symmetry work and the associated charm quantum number resulted; simultaneously, many new explanations for these particles appeared in the literature. It is premature to attempt a critical review of the various somewhat loosely structured ideas and specific models concerned with these unexpected new members of the particle family. Nevertheless, there are existing experimental data and some well-established theoretical ideas which are of interest and can be emphasized.

To put things in perspective, a brief review of those of our earlier considerations[4] which do not overlap the work contained in a recent review paper[5] seems appropriate. The obvious reaction to consider for the investigation of the strong-interaction properties of the $J(\psi)$, ψ', and ψ'' seemed to be photoproduction.[6,7] We therefore first studied phenomenologically the vector-meson-photon ($V-\gamma$) coupling constants. Instead of the perfect SU(4) symmetry relation, $\gamma_\rho^{-2}:\gamma_\omega^{-2}:\gamma_\varphi^{-2}:\gamma_{J(\psi)}^{-2}=9:1:2:8$, we found that the experimental data satisfied a modified relation[8]

$$\gamma_\rho^{-2}:\gamma_\omega^{-2}:\gamma_\varphi^{-2}:\gamma_{J(\psi)}^{-2}\simeq 9\frac{m_\omega}{m_\rho}:1:2\frac{m_\omega}{m_\varphi}:8\frac{m_\omega}{m_{J(\psi)}}, \tag{1}$$

where the electromagnetic current is given through vector-meson dominance (VMD) by $J_\mu^{\mathrm{em}} = -\sum_V m_V^2(2\gamma_V)^{-1}V_\mu$, with $V=\rho$, ω, φ, and J (ψ). The particular form of symmetry breaking indicated by Eq. (1) could not be simply explained by generalizing earlier considerations[9] on SU(3) symmetry-breaking effects in the V-γ couplings.

An analogy between the behavior of the J (ψ) and the φ meson has often been made,[4,5] since in the quark model for SU(4), the two are charmed and strange quark-antiquark pairs, respectively. This prompted us to examine the evidence on quark-line and quantum-number suppression of production and decay of the narrow resonances, particularly the φ meson, in order to gain a quantitative impression of the validity of the Zweig rule.[10] We tabulated[4] the experimental ratios of various ρ, ω, and φ production cross sections for $\pi^-p\to Vn$, $\pi^+p\to V\pi^+p$, $\pi^+p\to V\Delta^{++}$, etc., as a function of beam momentum. Strong suppression, by factors ranging from 25 to 300, are evident for φ production compared with ρ and ω production. This suppression, in the quark-model context, is due to interruption of quark-line flow. The ratios fluctuate considerably, so extraction of relations with predictive power is not possible; however, we do note that the cross section for ω production is typically a factor of two down compared with ρ production, but we will not pursue this here. K^--induced reactions which can proceed without quark-line-flow interruption show ρ, ω, and φ production cross sections to be of the same order of magnitude.

Drawing an analogy for the exceedingly narrow J (ψ), ψ', and others which may be found, one concludes that they must possess internal quantum numbers carried probably by constituents which are different from those making up the low-mass conventional mesons and baryons. Production of the J (ψ) and ψ' is therefore drastically suppressed in conventional accelerator reactions. Their appearance in electron-positron annihilation at energies very close to the observed increase in the ratio $R((e^+e^- \to \text{hadrons})/(e^+e^- \to \mu^+\mu^-))$ strongly suggests the opening of a threshold for particles with new quantum numbers. Our concern in this paper will be mainly with how these new particles are coupled with the photon.

From this general suppression of φ-production cross sections it has been deduced that φ photoproduction (plus VMD) provides direct information on Pomeron exchange.[11] In fact, analyses of various data yield considerable similarity between the Pomeron amplitude deduced from K^+p elastic scattering with that extracted from various (including φ) photoproduction reactions (assuming VMD).[12] In turn, the Pomeron contribution to K^+p scattering has been shown consistent with that which remains in pion-nucleon scattering when resonances are removed.[13] A crude test can be made (up to $\ln^2 s$ factors perhaps) for Pomeron dominance in φ photoproduction by assuming that the amplitude is a single exponential in t with $d\sigma/dt\,|_{t=0} \cong$ constant from essentially threshold, so that the energy behavior of the cross section near threshold is determined by the $t_{\min}$ effect. The general features, including the rise of the cross section from threshold of the $\gamma p \to \varphi p$ reaction, are in reasonable agreement with this naive picture.

This prescription does not translate all that successfully to photoproduction of the J (ψ). This naive view of Pomeron dominance leads one to expect that the measured values[14] of $d\sigma/dt\,|_{t'=0}$ for $\gamma p \to J(\psi)p$ might well follow the threshold energy behavior predicted by $\exp(bt_{\min})$. Figure 1 shows this not to be the case, except perhaps for

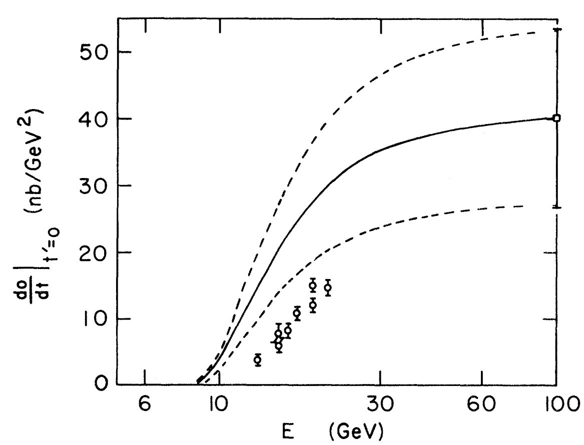

FIG. 1. Comparison of forward $J(\psi)$ photoproduction data (see Ref. 14) with naive Pomeron-dominance expectations. The dashed lines represent $\exp(4\,t_{\min})$ extrapolated back from the Fermilab limits with no additional threshold dependence added. If $\exp(2.9\,t_{\min})$ (see Ref. 14) is used, the curves will be higher for lower values of E.

the grossest features. The preferred band extrapolates down from the Fermilab datum point[15] at 100 GeV photon energy to lie consistently above the new data of Ref. 14. We note in passing that the values given in Ref. 14 for differential cross sections at $t=0$ and $t'=0$ do exhibit the systematic regularity, as a function of s in the threshold region,

$$\frac{d\sigma}{dt}\bigg|_{t=0} - \frac{d\sigma}{dt}\bigg|_{t'=0} \simeq \text{constant} = 3.9 \pm 0.5\ \text{nb/GeV}^2\,.$$

This is a compact way of detailing the shortcomings of the naive Pomeron-exchange description which is illustrated differently by Fig. 1. We shall pursue, in view of this failure, a more general approach to J (ψ) and heavier vector-particle photoproduction.

In the next section we discuss the photoproduction of vector-meson states and their relation with the total photoabsorption cross section. Our main observation from which several interesting consequences follow may be stated: If at any energy the nucleon photoabsorption cross section is known along with the photoproduction cross sections of the well-known vector mesons ρ, ω, φ, and ρ', then the Compton sum rule can be used to provide an upper bound at that energy on the photoproduction cross sections for all other $J^P = 1^-$ hadronic states including the J (ψ), ψ', etc., and the possible continuum contributions which may couple to the photon. Specifically, we find that a straightforward extrapolation of the SLAC photoabsorption measurements to higher energies as given by the experimenters results in saturation of the Compton sum rule in the Fermilab energy range by the ρ, ω, φ, and ρ' mesons. The final section has conclusions and discussion of our prediction: The forward proton Compton and total photoabsorption cross sections will exhibit a leveling off and rise in Fermilab experiments. Also discussed are the implications for the generalized vector-meson dominance treatment of deep-inelastic electroproduction and its scaling behavior due to this rising photoproduction cross section.

II. PHOTOPRODUCTION OF J (ψ) AND THE COMPTON SUM RULE

Conventional hadron reactions with single J (ψ) production or J (ψ) pair production are expected to be strongly suppressed. Photoproduction at present appears to be the best alternative to e^+-e^- colliding-beam experiments for observation of these particles in usual accelerator reactions. Should the reaction be diffractive as expected, s-channel helicity conservation and exponential

t falloff will be found. Indeed, measurements have recently been performed and hadronlike cross sections for total J (ψ)-proton scattering have been deduced.[14-16] In this section we shall use the Compton sum rule to examine if saturation occurs and turn the sum rule around to set upper limits on the J (ψ) photoproduction or that of any other 1^- hadron states which may couple to the photon (in addition to ρ, ω, φ, and ρ'). The input needed to achieve this objective are standard VMD and quark-model results which we summarize briefly in the following.

(i) For vector-meson (V) photoproduction[17]

$$\frac{d}{dt}\sigma^0(\gamma p\to Vp)=\frac{4}{\alpha}(\gamma_V^2/4\pi)^{-1}\frac{d}{dt}\sigma^0(Vp\to Vp)$$
$$=\frac{\alpha}{64\pi}(\gamma_V^2/4\pi)^{-1}(1+\eta_V^2)\sigma_T^2(Vp), \tag{2}$$

where the superscript 0 is used to denote quantities evaluated at $t=0$, which is nearly physical ($\theta=0^0$) for very high energies. The ratio of real to imaginary parts at $t=0$ for Vp scattering is denoted by η_V, α is the fine-structure constant, and the subscript T denotes total cross section.

(ii) The Compton sum rule relating the total photon-proton scattering to vector-meson photoproduction is

$$\sigma_T(\gamma p)=\sum_V\left[4\pi\alpha\left(\frac{\gamma_V{}^2}{4\pi}\right)^{-1}(1+\eta_V{}^2)^{-1}\frac{d}{dt}\sigma^0(\gamma p\to Vp)\right]^{1/2}$$
$$=\sum_V\frac{\alpha}{4}\left(\frac{\gamma_V{}^2}{4\pi}\right)^{-1}\sigma_T(Vp)\,. \tag{3}$$

We further define

$$\sigma_{\rm rhs}\equiv\sum_{V=\rho,\omega,\varphi,\rho'}\frac{\alpha}{4}\left(\frac{\gamma_V{}^2}{4\pi}\right)^{-1}\sigma_T(Vp) \tag{4}$$

and

$$\delta\equiv\sigma_T(\gamma p)-\sigma_{\rm rhs}\,. \tag{5}$$

(iii) The additive-quark-model relations for SU(4) are

$$\sigma_T(\rho p)=\sigma_T(\omega p)=\tfrac{1}{2}[\sigma_T(\pi^+p)+\sigma_T(\pi^-p)]\,, \tag{6}$$

$$\sigma_T(\varphi p)=\sigma_T(K^+p)+\sigma_T(K^-n)-\sigma_T(\pi^+p)$$
$$=\sigma_T(K^+n)+\sigma_T(K^-p)-\sigma_T(\pi^-p)\,, \tag{7}$$

$$\sigma_T(J(\psi)p)=\sigma_T(D^+p)+\sigma_T(D^-n)-\sigma_T(\pi^+p)$$
$$=\sigma_T(D^+n)+\sigma_T(D^-p)-\sigma_T(\pi^-p)$$
$$=\sigma_T(F^+p)+\sigma_T(F^-p)-\sigma_T(\varphi p)$$
$$=\sigma_T(F^+n)+\sigma_T(F^-n)-\sigma_T(\varphi p) \tag{8}$$

where D and F are pseudoscalar charmed mesons predicted by SU(4) symmetry resulting from the addition of a fourth charmed quark to the usual three-quark scheme.[5] These relations involve only the assumption of additive quark counting and spin independence. The additional requirements often used, such as the Pomeranchuk theorem for the $I=1$ amplitude or the isospin independence of nonstrange noncharmed quark-quark scattering, are not needed. Since $\sigma_T(J(\psi)p)$ is bigger than zero,[15] Eq. (7) leads to bounds on the sums $\sigma_T(DN)+\sigma_T(\overline{D}N)$ and $\sigma_T(FN)+\sigma_T(\overline{F}N)$. With $\sigma_T(J(\psi)p)\approx 1$ mb,[15] we have, invoking the approximate validity of the Pomeranchuk theorem at Fermilab energies, $\sigma_T(D^+N)\approx D_T(D^-N)\simeq 12-13$ mb and $D_T(F^+N)\simeq 6-7$ mb. If SU(4) turns out to be approximately valid, these numbers can serve as tests of the additive quark model in this scheme.

The general situation with regard to determinations of the couplings $\gamma_V{}^2/4\pi$ is summarized nicely by Wolf.[17] The Orsay-storage-rings measurements of $\gamma_V{}^2/4\pi$ ($V=\rho,\omega,\varphi$) turn out to agree very adequately with results obtainable from experimental values of $d\sigma^0(\gamma p\to Vp)/dt$ plus the quark model. However, the same basic calculation with the further assumption that ρ,ω,φ production dominates the intermediate states (in fact, the ρ^0 contribution itself is ~65% of the sum rule) between the incident and outgoing forward photon leads to much smaller, unacceptable values. Thus, other vector mesons including the J (ψ), ψ', etc., and perhaps $J^P=1^-$ continuum contributions must enter into the sum rule. With the Orsay $\gamma_V{}^2/4\pi$ values[17] and the total γp cross section[18]

$$\sigma_T(\gamma p)=(98.7\pm 3.6)+(65.0\pm 10.1)E_\gamma{}^{-1/2}, \tag{9}$$

then for $E_\gamma=9.3$ GeV, $\sigma_T(\gamma p)=120$ μb; $\sigma_{\rm rhs}$ defined in Eq. (4) is

$$\sigma_{\rm rhs}=[(74.8\pm 6.3)_\rho+(9.1\pm 1.0)_\omega$$
$$+(6.0\pm 0.3)_\varphi+(11.7\pm 2.7)_{\rho'}]\,\mu{\rm b}$$
$$=101.6\pm 6.8\ \mu{\rm b},$$

where $\eta_V{}^2$ has been neglected.

The difference, Eq. (5), at 9.3 GeV is

$$\delta=18.4\pm 6.8\ \mu{\rm b}=0.93\pm 0.34\ \mu{\rm b}^{1/2}/{\rm GeV}. \tag{10a}$$

If we use the $\gamma_V{}^2/4\pi$ values given by Martin *et al.*,[16] this difference reduces to

$$\delta'=14.3\ \mu{\rm b}=0.72\ \mu{\rm b}^{1/2}/{\rm GeV}. \tag{10b}$$

δ or δ' is the unaccounted for cross section at $E_\gamma=9.3$ GeV for photoproduction of all 1^- states (continuum and resonances) which couple to the

TABLE I. Parameters describing the total cross section $\sigma_T = a + b p_{\text{lab}}^{-n} + c \ln^2(p_{\text{lab}}/50)$ for $\pi^{\pm}p$, $K^{\pm}p$, and $K^{\pm}n$. (σ_T in mb and p_{lab} in GeV/c.)

σ_T	a	b	n	c
$\pi^+ p$	22.88 ± 0.18	2.82 ± 1.67	0.604 ± 0.300	0.378 ± 0.052
$\pi^- p$ [a]	28.12 ± 0.08	9.14 ± 0.49	0.559 ± 0.034	0.347 ± 0.012
$K^+ p$ [b]	16.70 ± 0.14	0.133 ± 0.051	-0.598 ± 0.066	0
$K^+ n$ [b]	16.99 ± 0.45	0.135 ± 0.146	-0.581 ± 0.181	0
$K^- p$	19.98 ± 0.07	10.69 ± 1.28	0.865 ± 0.065	0.398 ± 0.038
$K^- n$	19.73 ± 0.08	16.47 ± 3.69	4.67 ± 1.20	0.279 ± 0.050

[a] These values represent a fit with Fermilab data weighted to emphasize the increasing cross section over the falling trend represented by Serpukhov measurements.

[b] Fits with the rising cross section in our required energy range could be readily obtained by lowering the scale energy in the $\ln^2$ term. For example, $\sigma(K^+n)$ is satisfactorily represented (χ^2 probability >20%) by $\sigma(K^+n) = 17.1 \text{ mb} + 0.93 \text{ mb} \ln^2 p_{\text{lab}}$ or $\sigma(K^+n) = 17.3 \text{ mb} + 0.115 \text{ mb} \ln^2(p_{\text{lab}}/2)$.

photon when ρ, ω, φ, and ρ' are removed. With $t_{\min} = -0.786 \text{ GeV}^2$, $b = 5 \text{ GeV}^{-2}$ for the forward diffractive slope for φ photoproduction, and converting the entire amount of δ, Eq. (10a), into single 1^- meson production, we get

$$\sigma(\gamma p \to 1^- p) \approx b^{-1}(d\sigma^0/dt)\exp(b t_{\min}) \leq 0.095 \pm 0.070 \ \mu\text{b}$$

and $\sigma_T(1^- p) \leq 25.2 \pm 9.4$ mb, where, for definiteness we used $\gamma_V^2/4\pi = 3.25$, the J (ψ)-γ coupling constant for this "1^-"-photon coupling. If δ', Eq. (10b), is used, one gets $\sigma(\gamma p \to 1^- p) \leq 0.056$ μb.

These upper limits are all considerably larger than the measured values for J (ψ) or ψ' photoproduction near (above) 9.3 GeV, or, the J (ψ) and ψ' contribute negligibly to the Compton sum rule at 9.3 GeV. Does this situation change as photon energy is increased? In the SLAC energy range the measured photoabsorption cross section is falling relatively rapidly compared with the photoproduction data available at similar energies. Therefore, a more stringent bound than that at 9.3 GeV will certainly be found at the highest SLAC energies and particularly beyond the SLAC range if we use the analytical form, Eq. (9), given by the experimenters to extrapolate into the Fermilab energy range where these experiments are yet to be done. The quantity δ of Eq. (5) is seen to be decreasing with increasing energy, implying that the cross section available for missing 1^- states including 1^- continuum is decreasing. To calculate δ when insufficient data exist at these high photon energies we do the following.

(a) Since photoproduction cross sections of vector mesons do not exist at Fermilab energies, we use the quark-model relations given in Eqs. (6) and (7). For this purpose we fitted the existing $\pi^{\pm}p$, $K^{\pm}p$, and $K^{\pm}n$ total cross-section data from laboratory momentum p_l near 5 GeV/c to 200 GeV/c with the form[19]

$$\sigma_T = a + b p_l^{-n} + c \ln^2(p_l/50). \tag{11}$$

Although the terms appearing in this expansion are very familiar, we emphasize that the only validity we claim for Eq. (11) is the smooth representation of fluctuating data it generates for use in Eqs. (6) and (7). The values obtained for the parameters in Eq. (11) are listed in Table I.

(b) The photon-proton total cross section is represented by Eq. (9) which is valid into the Serpukhov energy range.[18] For comparison purposes we also use the slightly different form published by the same authors[20]

$$\sigma_T(\gamma p) = (94.1 \pm 3.5) + (79.0 \pm 10.0) E_\gamma^{-1/2}. \tag{12}$$

These parametrizations, Eq. (9) and Eq. (12), will be extended beyond the range of currently available Compton data. We feel justified in doing this as even a crude estimate of the amount of J (ψ) and heavier meson photoproduction is worth obtaining, and, furthermore, theoretical analyses[21] already exist which require the validity of the forms Eqs. (9) and (12) out to $E_\gamma = \infty$. Conflicts with the sum rule could indicate too where deviations from the forms (9) and (12) will occur.

(c) Information on the ρ' is becoming available, and the fact that it is diffractively produced[22] justifies our assumption of constant cross section. Therefore we use the photoproduction ρ' cross section measured at 9.3 GeV up to Fermilab energies. The ρ and ω contributions dominate considerably over the ρ', so that if the ρ' photoproduction cross section should turn out to increase at high energies (as those for the ρ and ω do by our quark-model calculation), only a small error will have been made.

These "known" contributions to the Compton sum rule are illustrated in Fig. 2. The total γ-p cross sections are the solid lines calculated from Eqs. (9) and (12). These are simply published[18,20] fits to the same data; the uncertainty on these curves is not indicated, although in the energy range of the data it is readily calculated to be about five percent. The deviation at large energy of the two curves serves to indicate uncertainty in the large-energy extrapolation. The dashed lines indicate the contribution to the right-hand side of the sum rule, Eq. (3), from the usual vector mesons, ρ, ω, φ, and ρ', calculated for Orsay γ-V couplings as tabulated by Wolf (labeled D) and $\gamma_V{}^2$ of Martin *et al.*[16] labeled as C. The uncertainties in the curves are about 5%, due mainly to errors in $\gamma_V{}^2/4\pi$. With curves as drawn (and taken literally), the difference between a solid line and a dashed line immediately yields [by VMD, Eq. (3)] upper limits for

$$\sigma_T(1^-p),\ \frac{d\sigma^0}{dt}(\gamma p \to 1^-p),\ \frac{d\sigma^0}{dt}(1^{-1}p \to 1^-p),$$

etc., for the unaccounted-for 1^- states, by assuming a diffractive slope and a 1^--γ coupling constant. More precisely, the difference of a solid and dashed curve gives the contributions for all heavier vector mesons and continuum to the sum rule. The sets of curves cross over each other at Fermilab energies and possibly already at the uppermost Serpukhov energies. However, according to the sum rule, the dashed curves should always be below the solid curves representing $\sigma_T(\gamma p)$. This implies that either the "theoretical" dashed curve or the extended experimental solid curve, or both, must change their trend at Fermilab energies. Some interesting consequences of this observation will be discussed next.

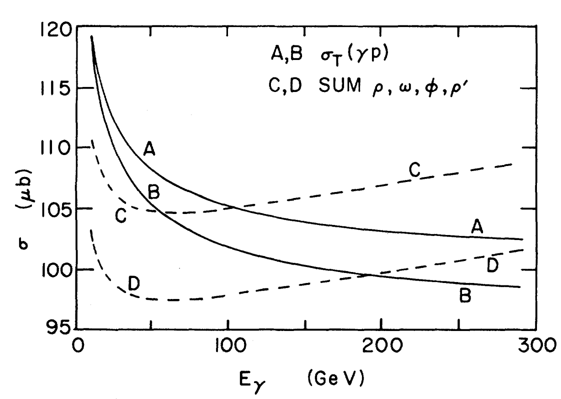

FIG. 2. Plots of the total photon-proton cross section extrapolated from analytical fits to the data below E_γ =18 GeV from (A) Ref. 17 and (B) from Ref. 20. Curves (C) and (D) are the contributions to the Compton sum rule of the ρ, ω, φ, and ρ' mesons using the (D) Orsay $\gamma_V{}^2/4\pi$ values from Ref. 17 and (C) the Martin *et al.* values of Ref. 16.

III. DISCUSSION AND CONCLUSION

A. Rising photon-proton cross sections.

At SLAC and Serpukhov energies, the difference between $\sigma_T(\gamma p)$ and the contribution of the sum of the known vector mesons, including ρ, ω, φ, ρ', J (ψ), and ψ', is large, of the order of $10 \sim 15$ μb; it decreases rapidly in the Fermilab energy range, as illustrated in Fig. 2. Independent of which set of $\gamma_V{}^2/4\pi$ is used, the total photoabsorption cross section, according to our calculations, will be saturated, even oversaturated, by ρ, ω, φ, and ρ' at Fermilab energies. Taken literally, this implies that the photoproduction of high-mass vector mesons will cease and that the photon will decouple from such states between ~50 and 300 GeV photon energy. The logical solution removing this discrepancy is that $\sigma_T(\gamma p)$ departs from its steadily decreasing trend between 2 GeV and Serpukhov energies, levels off, and begins rising at Fermilab energies. It seems natural from the photon-hadron analogy that $\sigma_T(\gamma p)$ should follow the same pattern as the hadron total cross sections.

However, if it should turn out that $\sigma_T(\gamma p)$ fails to rise in the Fermilab energy range, in addition to decoupling of high-lying vector states from the photon, there are other possibilities which might be responsible for the deviation of the sum rule. In addition, failure of $\sigma_T(\gamma p)$ to rise casts serious doubt upon the validity of VMD and/or the additive quark model, and upon the notion of nuclear democracy in the high-energy hadronic world. This follows since it is generally believed along with the coexistence of a possible underlying fundamental quark structure, that resonances like the ρ, ω, etc., interacting with protons at very high energies should not behave drastically differently than the stable particles, like pions, etc. Rising total cross section should not be a "local" phenomenon associated only with stable particles.

B. Generalized vector-meson dominance.

The negligible contributions of the J (ψ) and ψ' to the right-hand side of the Compton sum rule, Eq. (3), leaves an unaccounted for cross section of ~16% of $\sigma_T(\gamma p)$ at 9.3 GeV and a smaller amount at higher energies. This brings up the question of how the sum rule will be saturated or, differently, what are the other hadron constituents of the photon? Two suggestions can be drawn from the literature. (a) Generalized VMD suggests $\sigma_T(\gamma p)$ is saturated by infinitely many intermediate vector mesons, of both isovector and isoscalar types. The individual vector mesons with mass higher than a certain value will have a tiny contribution to the sum rule in order for the infinite series to converge. In this viewpoint, the small contributions of J (ψ) and ψ' can be understood if these particles are already in the "tail" of the infinite series. The application of the generalized VMD to electroproduction processes is referred to as illustrating a new duality principle; for elucidation one may refer to Sakurai's[23] lectures. (b) The unaccounted for cross section may be due to nonresonant continuum contributions, for example, the 2π continuum in the isovector part.[24] This will not be pursued further except for noting that such terms are certainly a part, at least, of δ, Eq. (5).

A test of this new duality in the sense of complete dominance of the hadronic part of the electromagnetic current by vector-meson poles can be made by examining the quantity δ, Eq. (5), as a function of photon energy. In the approach of Ref. 25 with a photon-mass dispersion relation,[23] the contribution of each vector meson is proportional to its on-shell total nucleon cross section. Therefore, at high energies, we expect that δ is a constant, modulo a logarithmic variation, in energy. This will be true in the case of the additive quark relations, if, for example, the γ-p cross section rises as

$$\sigma_T(\gamma p) \simeq \frac{\alpha}{\pi}[\sigma_T(\pi^+ p) + \sigma(\pi^- p)] \; .$$

If δ turns out to vary with energy significantly, we believe that the formulation or the ideas of the new duality need to be modified, e.g., by an energy-dependent background part, as in (b) mentioned above.

C. Scaling behavior.

The new duality and a rising photoabsorption cross section have further implications, as in the scaling behavior of electroproduction data. A somewhat simplified argument will illustrate the main points. We begin by writing

$$\begin{aligned} F_1(\omega, Q^2) &\equiv 2m_N W_1(Q^2, W^2) \\ &= \frac{1}{4\pi^2\alpha}\left(1-\frac{1}{\omega}\right)\omega Q^2 \sigma_{\mathrm{Tr}}\;(Q^2, W^2), \end{aligned}$$

where W_1 is one of two inelastic structure functions for ep collisions and σ_{Tr} (W^2, Q^2) is the transverse polarized virtual photon-proton cross section. The kinematic factors are standard; q $(Q^2 \equiv -q^2)$ is the virtual-photon momentum, W the virtual-photon–proton total energy, and ω is the scaling variable. They are related by

$$W^2 = m_N{}^2 + Q^2(\omega - 1) \, .$$

An approximate expression[24] for σ_{Tr} gives

$$\sigma_T(W^2, q^2) = \frac{m_{\mathrm{th}}{}^2}{m_{\mathrm{th}}{}^2 + Q^2}\,\sigma_{T,\,\gamma p}(W^2),$$

where $m_{\mathrm{th}}{}^2 \simeq 0.37$ GeV^2 is some effective threshold. Now, for $Q^2 \gg m_N{}^2$, $\omega \gg 1$,

$$F_1(\omega, q^2) \simeq \frac{m_{\mathrm{th}}{}^2}{4\pi^2\alpha}\left(1-\frac{1}{\omega}\right)\omega\sigma_{T,\gamma p}[Q^2(\omega - 1)] \; .$$

We see that scaling is obtained if $\sigma_{T,\gamma p} \to$ const at large Q^2. However, if $\sigma_{T,\gamma p}(W^2) \propto (\ln W^2)$, as expected from the present analysis and the trend in hadron reactions, a $\ln^2 Q^2$ scaling breaking results. If $\sigma_{T,\gamma p}$ continuously increases logarithmically such as to saturate the Froissart bound, then a permanent logarithmic violation of scaling is implied. A detailed examination of this question should be carried out when a more precise formulation of the new duality is achieved.

The discovery of the vector mesons with masses above 3 GeV has forced us to think more sharply about the 1^- states that can couple to the photon. The Compton sum rule provides the means for determining the cross-section limits for these states and making predictions on the high-energy behavior of the photon-proton cross section. We see three current interesting ideas being interconnected through this work; rising cross sections for proton photoabsorption at Fermilab energies, a test of the "new" duality for generalized VMD, and a possible permanent violation of scaling implied by these first two points. This makes us anticipate with great interest experiments on vector-meson photoproduction and Compton scattering at Fermilab.

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