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Photon-proton reactions

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We present a model based on quantum chromodynamics for calculating the photoproduction of particles containing heavy quarks. The production of heavy quarks is due to photon-gluon interaction. Soft-gluon emission is assumed to create a random-phase situation. The implications for vector dominance are discussed. Light-flavor production unlike heavy-flavor production is vector-meson dominated.

I. INTRODUCTION

The production of particles made of c and b quarks has been calculated by us for proton-proton interaction in a previous paper[1] using quantum-chromodynamics (QCD) and quarkonium considerations. We extend the model, in this paper, to photon-proton interactions. The usual treatment[2,3] for calculating the production of c-flavored or b-flavored states is to calculate the cross section for production of a heavy-quark–antiquark pair by constituent annihilation. The contributions above $D\bar{D}$ or $B\bar{B}$ threshold are identified with the cross section for production of D or B mesons, respectively. The production of ψ is often identified with the rate of $c\bar{c}$ production below $D\bar{D}$ threshold divided by the number of bound states.

Our treatment differs from other QCD calculations[2,3] in that for the case of $D\bar{D}$ production we calculate the rate of $c\bar{c}$ production followed by the capture of two light sea quarks and similarly for $B\bar{B}$ production. Perhaps somewhat frivolously we extend the calculations to $K\bar{K}$ production. Our model, which was successful in describing the production of $Q\bar{Q}$ mesons with $Q=c,b$ in proton-proton interactions is extended here to photon-proton interactions. The model presumes that a produced $Q\bar{Q}$ pair becomes a bound state after gluon emission. There is expected to be a high probability for "soft"-gluon emission and absorption by the heavy quarks before the transition to a bound state by single-gluon emission. The rate for such a process is estimated using a dipole matrix element and nonrelativistic quarkonium wave functions. Most of the produced $Q\bar{Q}$ pairs lead to $D\bar{D}$, $B\bar{B}$, or $K\bar{K}$ production as the case may be. There is, however, a finite if relatively small probability that a bound state results. The soft-gluon emission is assumed to create a random-phase situation so that the relative rate for say ψ and $D\bar{D}$ production, or Υ and $B\bar{B}$ production, is determined by intensity ratios.

The extension of our model here to photon-proton reactions has implications for vector dominance. An explanation, within the framework of QCD, of how the total photon-proton cross section rises is given.

We discuss c-flavor, b-flavor, and strange-particle photoproduction in Sec. II and heavy-quark–antiquark bound-state production in Sec. III. Section IV is a discussion of the comparison of theory with experiment. The implications for vector dominance are discussed in Secs. V and VI. The rising cross section is also discussed in Sec. VI. Section VII contains a summary and conclusions.

II. $D\bar{D}$, $B\bar{B}$, AND $K\bar{K}$ PHOTOPRODUCTION

We now calculate $D\bar{D}$, $B\bar{B}$, and $K\bar{K}$ photoproduction. Lowest-order QCD yields the following result for $Q\bar{Q}$ production in photon-proton interactions[2,3]:

$$\sigma(s)=\int_0^1 g(x,xs)\hat{\sigma}(sx)dx\,, \tag{1}$$

where $\hat{\sigma}(sx)$ is calculated using the diagrams in Fig. 1,

$$\hat{\sigma}(\hat{s})=\frac{8\pi\alpha\alpha_s(\hat{s})}{9\hat{s}^3}\left[(\hat{s}^2+4m_Q{}^2\hat{s}-8m_Q{}^4)\ln\left(\frac{\hat{s}+\Lambda}{\hat{s}-\Lambda}\right)-(\hat{s}+4m_Q{}^2)\Lambda\right], \tag{1a}$$

with

$$\Lambda=(\hat{s}^2-4m_Q{}^2\hat{s})^{1/2},\quad \hat{s}=sx\,.$$

We use for $g(x,xs)$ and $\alpha_s(\hat{s})$ the parametrization from deep-inelastic lepton scattering.[4] Nonscaling effects[5] are important in Eq. (1).

The heavy produced $Q\bar{Q}$, for the most part, capture each a light quark to produce $D\bar{D}$, $B\bar{B}$, and $K\bar{K}$ as the case may be. Therefore, we identify such production with $Q\bar{Q}$ pair production. However, our model[1] requires that the threshold for production be taken as double the mass of the quark Q, not twice the mass of the produced mesons. The remainder of the mass derives from the light-quark energy. The capture rate of the light quarks is unimportant here because the production of $D\bar{D}$,

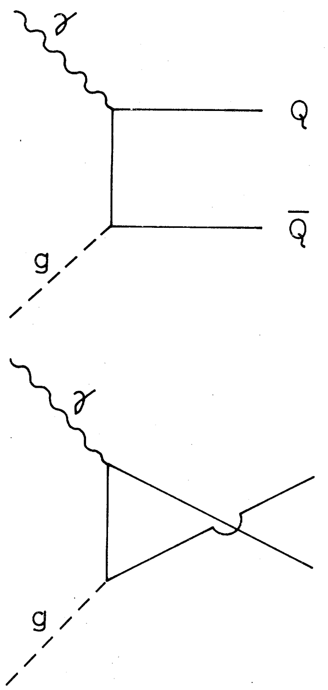

FIG. 1. Diagrams for the production of $Q\bar{Q}$ by photon-gluon fusion.

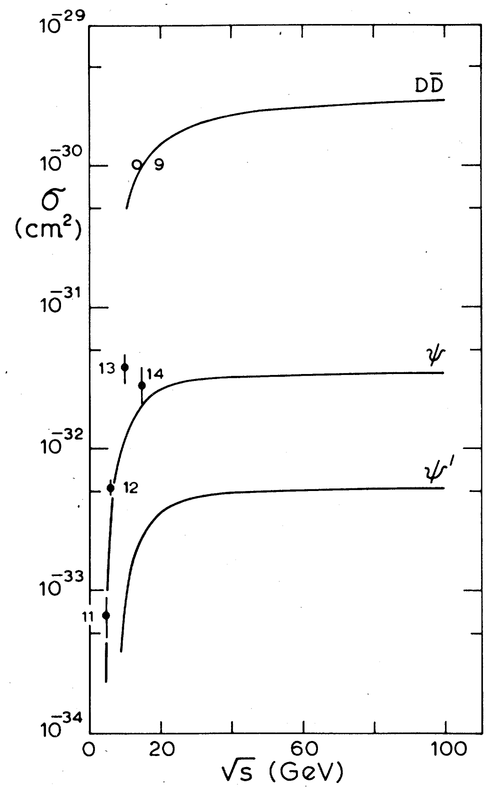

FIG. 2. The curves labeled ψ and ψ' represent our predictions for $\psi(3.1)$ and $\psi'(3.685)$ production cross sections in photon-proton interaction as a function of $\sqrt{s}$. These results are obtained using (see text and Ref. 1) $\xi = 0.42$ GeV, $m_c = 1.2$ GeV, $T = 0.15$ GeV, $N = 0.2$. The curve labeled $D\bar{D}$ corresponds to the $D\bar{D}$ production cross section in photon-proton interaction evaluated in QCD with $m_c = 1.2$ GeV; closed circles indicate the experimental data points for $\sigma(\gamma p \to \psi p)$ (Refs. 11–14). The number attached to each point indicates the experimental reference. The open circle indicates the data point for $D\bar{D}$ photoproduction (see text and Ref. 9).

$B\bar{B}$, or $K\bar{K}$ is dominant. The rate for capture of light quarks is, however, all important for the production of $Q\bar{Q}$ bound states in competition with the dominant processes. We discuss the light-quark capture rate in Sec. III, when we discuss photoproduction of quarkonium.

Figures 2, 3, and 4 show our calculated cross sections for $D\bar{D}$, $B\bar{B}$, and $K\bar{K}$ photoproduction using quark masses obtained from our earlier fits to proton-proton interaction[1] production of heavy-quark systems. In fact, all the parameters used in this paper are those from Ref. 1. The quark masses as given in the figure captions are slightly on the small side but not by more than 10 to 20%.

III. HEAVY $Q\bar{Q}$ BOUND-STATE PRODUCTION

We follow methods similar to those used for p-p interaction in Ref. 1 to calculate the photoproduction of $Q\bar{Q}$ bound states. Our procedure is to multiply the cross section for photoproduction of free $Q\bar{Q}$ pairs as calculated using lowest-order QCD at a given $\hat{s}$ by the branching ratio R_1/R_2. Here R_1 is the rate for decay of a free $Q\bar{Q}$ pair to a $Q\bar{Q}$ bound state by emission of a gluon and R_2 the rate of capture of one light sea quark by the Q or $\bar{Q}$ quark.

Following Ref. 1 we use an effective Hamiltonian[6] which induces gluon emission for the perturbing interaction and nonrelativistic wave functions for the $Q\bar{Q}$ system. The initial state is taken to be a plane wave of relative motion and the final state is taken to be a bound state in a harmonic-oscillator potential with frequency chosen to yield the right spacing between lowest S-state levels. The effective perturbing interaction which induces gluon emission is given by[6]

$$V_{\rm eff} = g\Lambda_a \overleftrightarrow{\nabla}\cdot\vec{A}_a(0)\,, \tag{2}$$

where g is the strong coupling constant, $\vec{A}_a(0)$ the transverse color gauge field, and $\Lambda_a = \frac{1}{2}(\lambda_a + \lambda_a^*)$ the color matrices for Q and $\bar{Q}$. The rate

$$R_1 = |\langle f | V_{\rm eff} | i\rangle|^2 2\pi\delta(E_i - E_f - \omega)\frac{d^3k}{(2\pi)^3 2\omega}\,, \tag{3}$$

where $|i\rangle$ and $|f\rangle$ are the initial and final $Q\bar{Q}$ wave functions having energy eigenvalues E_i and E_f, and

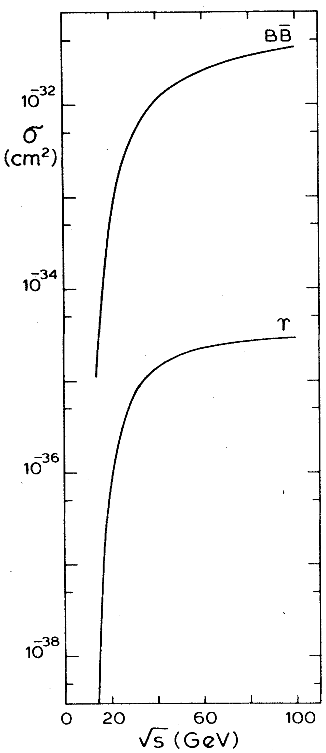

FIG. 3. The curve labeled Υ represents our prediction for Υ(9.46) production cross section in photon-proton interaction as a function of $\sqrt{s}$. This result is obtained using $\xi=0.8$ GeV, $m_b=4$ GeV, $T=0.15$ GeV, $N=0.2$, and $\sigma_{qb}\simeq m_c^2/m_b^2\,\sigma_{qc}$ (see text and Ref. 1). The curve labeled $B\bar{B}$ represents the $B\bar{B}$ production cross section in photon-proton interaction evaluated in QCD with $m_b=4$ GeV.

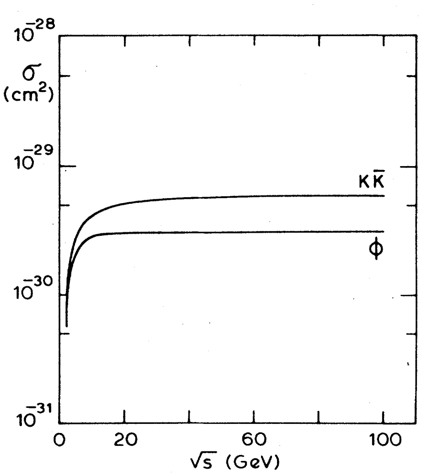

FIG. 4. The curve labeled ϕ represents our prediction for ϕ(1020) production cross section as a function of $\sqrt{s}$. The following values have been used. $\xi=0.19$ GeV, $m_s=0.4$ GeV, $T=0.15$ GeV, $N=0.2$, and $\sigma_{qs}\simeq m_c^2/m_s^2\sigma_{qc}$. The curve labeled $K\bar{K}$ represents our QCD prediction for $K\bar{K}$ production.

$(\omega,\vec{k})$ is the four-momentum of the emitted gluon. Summing over color and spin of the quarks and gluons one gets, following Ref. 1,

$$R_1^{J/\psi}=\bar{\alpha}_s(\sqrt{\hat{s}}-m_\psi)^3\frac{1}{V}e^{-P^2/\xi_c^2}(\hat{s}-4m_c^2)\frac{8}{27}\pi^{3/2}\frac{1}{\xi_c^7}, \tag{4}$$

where $\bar{\alpha}_s$ is the analog of α_s for soft gluons and taken to be 1 in the following: V is the volume in the box normalization of the initial $Q\bar{Q}$ wave function with three-momentum $P=\frac{1}{2}(\hat{s}-4m_c^2)^{1/2}$, and $\xi=(\frac{1}{2}\omega_0 m_c)^{1/2}$ with ω_0 the spring frequency. This result when multiplied by the relative spin statistical weight $\frac{1}{3}$ also describes η_c production. We use the same formulas for Υ and ϕ production, changing the quark and vector-meson masses and ω_0 appropriately. In excited-state production we have only to use the appropriate simple-harmonic-oscillator bound-state wave function in formula (3). For example,

$$R_1^{\psi'}=\bar{\alpha}_s(\sqrt{\hat{s}}-m_{\psi'})^3\frac{1}{V}e^{-P^2/\xi_c^2}(\hat{s}-4m_c^2)\times\left(\frac{2P^2}{\xi_c^2}-7\right)^2\frac{4}{81}\frac{\pi^{3/2}}{\xi_c^7} \tag{5}$$

and similarly for Υ′.

Following Ref. 1 we take the rate for light-quark capture to form D, B, or K as

$$R_2=\frac{N}{2V}\frac{\int e^{-P_q/T}\sigma_{qQ}^{\text{tot}}(\bar{s})(\bar{s}-m_Q^2)d^3P_q/E_qE_Q}{\int e^{-P_q/T}d^3P_q}, \tag{6}$$

where $\bar{s}=(p_q^\mu+p_Q^\mu)^2$, p_q^μ and p_Q^μ being the four-momenta of the light and heavy quarks, respectively, and p_q and p_Q are the magnitudes of the corresponding three-momenta. The cross section $\sigma_{qQ}^{\text{tot}}(\bar{s})$ is the total cross section for $\bar{q}$ incident on Q determined using experimental data for photoproduction on complex nuclei[7,8] and associated phenomena. This cross section is approximated to be zero below threshold for production of the appropriate pseudoscalar (e.g., D when $Q=c$) and constant above threshold. We also make use of the additive quark model. For b quarks we take[8] $\sigma_{qb}/\sigma_{qc}=m_c^2/m_b^2$. The quantity N is the number of light sea quarks or antiquarks in the proton-proton system assumed thermodynamically distributed at temperature T in the center of mass of the gluon-gluon system. The motivation for assuming such a distribution, as was pointed out in Ref. 1, is the following: The light quarks, for the most part, are emitted in combination with other light quarks as pions and ρ mesons. Their transverse-momentum distributions are well described, for the most part, by the form $e^{-P_T/T}$. The longitudinal distributions are more complicated, involving the gluon distributions in this picture. Finally, we arrive at the result for production of the heavy $Q\bar{Q}$ bound state M_i, given by

$$\sigma(\gamma + P \to M_i + X) = \int_0^1 dx\, g(x,\hat{s})\sigma(\hat{s}) R_1^{M_i}(\hat{s})/R_2^{M_i}(\hat{s}) ,$$

where $\hat{s} = xs$ and $g(x,\hat{s})$, $\sigma(\hat{s})$ are as defined in Eqs. (1) and (1a).

IV. COMPARISON WITH EXPERIMENT

The results for $\psi(3.1)$ photoproduction calculated above agree quite well with experiment, as can be seen in Fig. 2. The data points in Fig. 2 are from $\gamma p \to \psi p$. We argue that the gluon represents the behavior of the Pomeron at very low values of x, the fraction of momentum of the proton carried by the gluon. We show in Fig. 5 the average x, $\langle x\rangle_{\gamma p}$, that contributes to our calculation of the photoproduction of ψ, compared to the average fraction of momentum carried by each gluon in the similar process[1] in p-p collisions, $\langle x\rangle_{pp}$. We might attribute the dominance of the exclusive channel in photoproduction of ψ to the smallness of $\langle x\rangle_{\gamma p}$. A preliminary experimental result[9] for photoproduction of D mesons at $s \simeq 188$ GeV^2 is well described by our calculations plotted in Fig. 2.

All the parameters used here in our calculations are taken over from our earlier calculations[1] of the production of the same particles in p-p interaction. These are $m_c = 1.2$ GeV, $T = 150$ MeV, $N = 0.2$, and $\xi = 0.42$ GeV [which follows from the $\psi(3.1)$, $\psi'(3.685)$ spacing]. The results are rather insensitive to T. Figure 3 shows our predictions for photoproduction of $\Upsilon(9.46)$. We adjust $\xi = 0.8$ GeV to the Υ, Υ' spacing as in Ref. 1 and use the same quark mass obtained fitting p-p production of Υ, $m_b = 4$ GeV.

We have also calculated $K\bar{K}$ and $\phi(1020)$ production in our model. The results are shown in Fig. 4. We use $\xi = 0.19$ GeV and $m_s = 0.4$ GeV as in p-p interaction.[1]

A feature of the heavy-quark production calculated as above is that it tends to a finite limit at very high energies compared to the predicted logarithmic rise in p-p interaction.

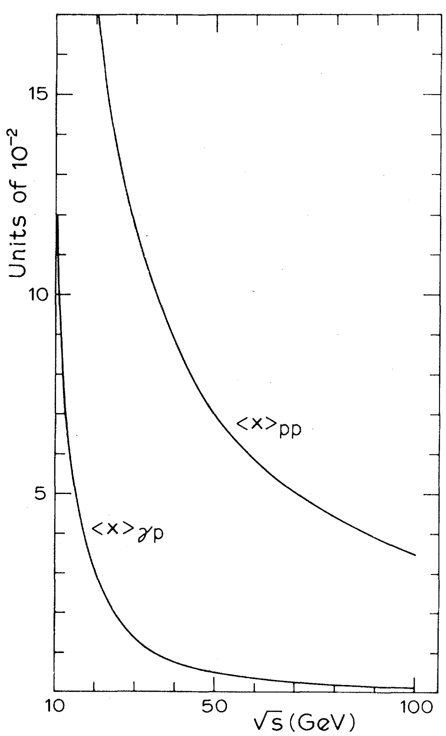

FIG. 5. The upper curve corresponds to the average fraction of momentum carried by each gluon on p-p collisions, $\langle x\rangle_{pp}$. The lower curve represents the average x for photon-production, $\langle x\rangle_{\gamma p}$.

V. VECTOR DOMINANCE AND HEAVY-QUARK PRODUCTION

We see in Figs. 2–4 that the ratio of the quarkonium state (ψ, Υ, ϕ) to pseudoscalar (D, B, K meson) photoproduction is very small for heavy quarks and increases strongly for lighter and lighter quarks. One might expect that, since for strange quarks the ratio of photoproduction of ϕ to K mesons is close to unity, for u and d quarks, if we could calculate things well, the production would be dominated by ρ and ω mesons.

An implication of this vector dominance for heavy-flavor production would be that the diagram in Fig. 6(a) could be approximated by diagram 6(b), where the vector meson V emits an "on-shell" gluon. We now take for the gluon distribution in the dominating vector mesons, that often used for pions,

$$g(x) = 2(1-x)^3/x . \tag{7}$$

Then using

$$\sigma(\hat{s})^{gg\to Q\bar{Q}} = \frac{\pi\alpha_s^2}{3\hat{s}^3}\left[(\hat{s}^2 + 4m_Q^2\hat{s} + m_Q^4)\ln\left(\frac{\hat{s}+\Lambda}{\hat{s}-\Lambda}\right) - (7\hat{s} + 31m_Q^2)\frac{\Lambda}{4}\right] , \tag{8}$$

where

$$\Lambda = (\hat{s}^2 - 4m_Q^2\hat{s})^{1/2} ,$$

as calculated from the diagrams in Fig. 7 we get

$$\sigma(\gamma + p \to \psi + X) = \bar{\alpha}\int_0^1 g(x_1)g(x_2)\sigma(x_1x_2s) \times \frac{R_1^{\psi}(x_1x_2s)}{R_2^{D}(x_1x_2s)} dx_1 dx_2 , \tag{9}$$

with $\bar{\alpha} = 4\pi\alpha(g_\rho^{-2} + g_\omega^{-2})$, where g_V^2 are the vector-dominance coupling constants.[10] Evaluation of the contribution of Eq. (9) to ψ production yields less

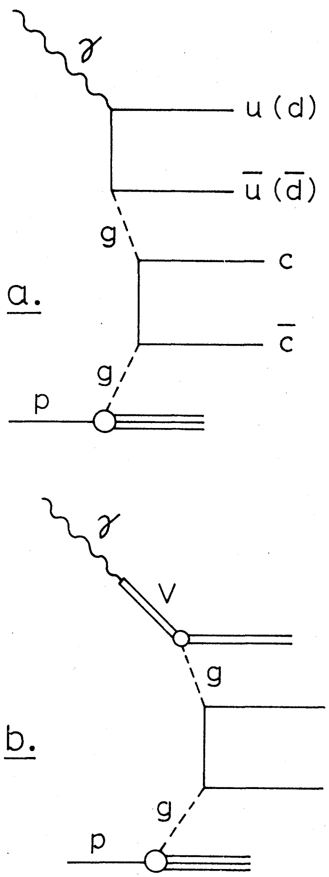

FIG. 6. Diagram (a) represents emission of light quarks (u, d) from the photon vertex together with production of $c\bar{c}$ quarks by gluon fusion. Diagram (b) represents the approximation to diagram (a) where the vector meson V emits an on-shell gluon.

than 1% of the amount evaluated using photon-gluon fusion as in formula (1). The reason for this small contribution is the smallness of the average subenergy $x_1 x_2 s$ in Eq. (9) compared to xs in Eq. (1). As far as heavy quarks are concerned, we conclude that their production is not influenced to any great extent by vector dominance since

(i) when a pair of heavy quarks is produced they rarely end up as a $Q\bar{Q}$ bound state, mainly because of the smallness of the form factor of the heavy $Q\bar{Q}$ system, and

(ii) when a ρ- or ω-like state dominates the photon it contributes less than 1% to the total heavy-quark production.

VI. VECTOR DOMINANCE AND PHOTON TOTAL CROSS SECTION

Suppose that even light-quark production by photons is not dominated by bound hadronic states, as opposed to the trend of the ratio of cross sections for production of quarkonium to open heavy-quark states, which was discussed in Sec. V. One could argue qualitatively that the total photon-proton cross section would be described by the lowest-order QCD diagrams shown in Figs. 1 and 8. In terms of valence quarks and gluon distributions one obtains

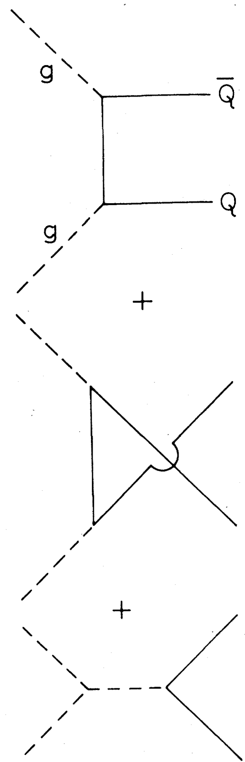

FIG. 7. These diagrams represent $Q\bar{Q}$ production by gluon-gluon fusion.

$$\sigma(\gamma p) = \int_0^1 dx\, g(x, xs)\sigma^g(xs) + \int_0^1 dx\, q(x, xs)\sigma^q(xs)\,. \tag{10}$$

We take $g(x, xs)$ and $q(x, xs)$ as given by Ref. 4. $\sigma^g(xs)$ is given in Eq. (1) and $\sigma^q(xs)$ (see Fig. 8) is

$$\sigma^q(xs) = e_Q{}^2 \frac{4}{3}\frac{\pi\alpha\alpha_s}{m_q k}\left\{\frac{1}{2} - \frac{1}{2[1+2(k/m)]^2} + \ln\left(1+2\frac{k}{m_q}\right) + \frac{2m_q}{k}\left[2 - \left(1+\frac{m_q}{k}\right)\ln\left(1+2\frac{k}{m_q}\right)\right]\right\}, \tag{10a}$$

where e_Q is the charge of the quark Q and k is given by

$$k = xs/2m_p \quad (m_p \text{ is the proton mass}). \tag{10b}$$

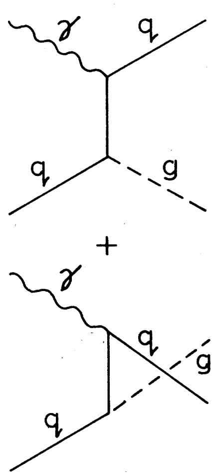

FIG. 8. Lowest-order QCD diagrams contributing to $\sigma^q(xs)$ [Eq. (10a)].

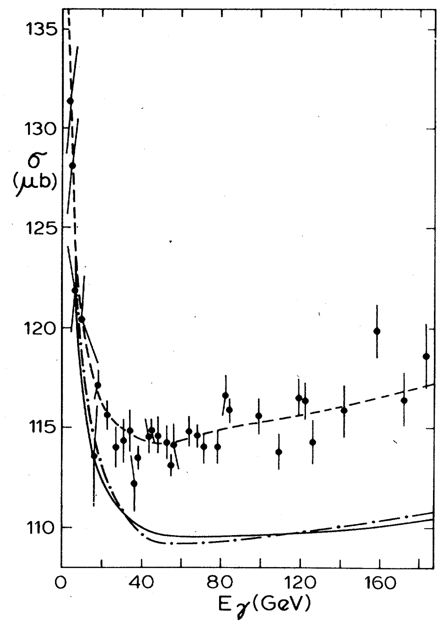

FIG. 9. The dashed curve represents a fit to the data (Ref. 15) for $\sigma_{\gamma p}$. The solid curve is obtained after subtracting $\sigma_{D\bar{D}}$ (see Fig. 2) and $\sigma_{K\bar{K}}$ (see Fig. 4) from the dashed curve. The dashed-dotted curve represents the total cross section $\sigma_{\rho p}$ multiplied by $C=\frac{1}{215}$. The curves are plotted as functions of the laboratory energy of the photon.

Even though the data (see Fig. 9) appear to have two components—one increasing with energy and the other decreasing—and the expressions in Eq. (10) are one (σ^g) increasing and the other (σ^q) decreasing, we are unable to fit the data using any values for the parameters for the various ingredients in Eq. (10). The crucial feature missing in Eq. (10) is that the γ-g term is not nearly strong enough to overcome the decrease in the qg term as implied by the data. Of course, higher-order QCD diagrams might help the situation. Rather than face this complication we turn back to the vector-dominance picture for light quarks.

Let us subtract from $\sigma_{\gamma p}^{\text{total}}$ the QCD contribution to strange- and charmed-quark photoproduction calculated above. The result is shown in Fig. 9. The cross section that remains is proportional to $\sigma_{\rho p}^{\text{total}}$, the total ρ-proton cross section calculated either using the spin-independent quark model or deduced using ρ-photoproduction experimental results. One finds striking confirmation of the vector-dominance picture for light quarks in Fig. 9.

The rising total photon cross section, over the energy range of interest, is seen to come in part from the rising cross sections for heavy-quark-meson production (see Figs. 2 and 4) and partly from the rise in the ρ-nucleon and ω-nucleon total cross sections, using vector dominance for light-quark photoproduction.

VII. SUMMARY AND CONCLUSIONS

A model developed earlier for heavy-flavor production in proton-proton reactions is used here to describe photon-proton heavy-flavor production. No readjustment of parameters is made and so the extension to photoproduction is parameter free. The implications for vector dominance are as follows: For heavy-flavor production, quarkonium vector states do not dominate the photon whereas the production of light-quark states is dominated by the light vector mesons. The origin of this difference is that the form factors of the light vector states allow for substantial coupling to real photons whereas for the heavy-quark systems the coupling is beat down more and more strongly by the quarkonium form factor as the quark mass increases.

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