PHYSICAL REVIEW D VOLUME 20, NUMBER 9 1 NOVEMBER 1979

Jets as a source for the observed increase in the γp cross section

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(Received 27 February 1979)

It is suggested that the dominant contribution to the observed increase in the γp cross section of 2 to 6 μb over the expectations of vector-meson dominance arises from the production of high-transverse-momentum jets and *not* charm as has been widely interpreted. The cross section for the production of three jets, one along the collision axis and two with high p_t, satisfactorily accounts for the deviation from ρ, ω, ϕ contributions. The charm component is found to be only a small fraction of the observed increase.

In a recent experiment at Fermilab, Caldwell *et al.*[1] measured the total γp cross section with tagged photons of laboratory energies up to $E_\gamma = 185$ GeV. They reported an increase in that cross section of ~2 to 6 μb over what one expects from a $(\rho+\omega+\phi)$ vector-meson-dominance (VMD) model (normalized to low-energy data). This increase has been widely interpreted to be due to the inclusive production of charm via the reaction $\gamma + p \to c + \bar{c} + x$[2-5] and as such it leads to several difficulties[6]:

(1) A quantum-chromodynamics (QCD) calculation for $\bar{c}c$ production, via photon-gluon fusion, yields cross sections (in the relevant energy range) of the order ≤ 0.7 μb.[7,8] This result is obtained using reasonable parameters, e.g., the mass of the charm quark $m_c \sim 1.5$ GeV, the quark-gluon fine-structure constant $\alpha_c(4\,m_c^2) \sim 0.3$, and a variety of forms for the gluon distribution function, $F_{p\gamma_c}(x)$, all normalized so that ($\gamma_c =$ gluon)

$$\int xF_{p\gamma_c}(x)dx = \tfrac{1}{2}\,. \tag{1}$$

(2) Calculations which are more phenomenological in nature such as generalized vector-meson dominance (GVMD),[4] extension of VMD to the ψ assuming a linear potential,[5] or those which are a hybrid between QCD and VMD[3], while successful in explaining the entire observed increase in γp cross section of 2 to 6 μb as due to $\bar{c}c$ production, run into difficulties when attempting to extend their treatment to deep-inelastic lepton scattering and badly overestimate νW_2 for $Q^2 \geq 5$ GeV^2.[6]

(3) In addition, such a large $c\bar{c}$ contribution in γp would imply $\approx(\alpha_c/\alpha)\times(2$ to $6)$ μb $\approx(80$ to $240)$ μb of charm production in hadronic collisions.[9] This is inconsistent with the present consensus among the experimental community which calls for a much lower estimate for charm contribution in hadronic reactions.[10]

In this paper we investigate the possibility that the dominant component to the increase in γp cross section arises from nonhadronic (that is non-VMD) interaction of photons with quarks and gluons. We evaluate the (lowest-order in α_c) contribution of high-transverse-momentum (p_t) jets induced by photons. Our calculations indicate that the cross section for producing jets with $p_t \gtrsim 1$ GeV rises with energy and has a value of a few μb for $E_\gamma \sim 25$ to 200 GeV.[11] Consequently we suggest that the observed increase in γp cross section is primarily a measure of the deviation of photons from vector-meson dominance which, by its very nature of being a diffractive type mechanism, fails to take into account the high-p_t phenomena. The charm contribution is found to be only a small fraction of the observed increase in γp cross section.

We write the total γp cross section in the form

$$\sigma^T_{\gamma p} = \sigma^V_{\gamma p} + \sigma^c_{\gamma p}\,, \tag{2}$$

where $\sigma^V_{\gamma p}$ is "noncalculable" within the QCD framework and is related to the hadronic cross section through the VMD[12] as

$$\sigma^V_{\gamma p} = \sum_{V=\rho,\,\omega,\,\phi} \frac{4\pi\alpha}{\hat{f}_V^{\,2}}\,\sigma(Vp)\,, \tag{3}$$

where $\hat{f}_V^{\,2}/4\pi$ denote the vector-meson-photon coupling constants obtained from A-dependent experiments.[13] In addition one assumes the quark-model relations

$$\begin{aligned} &\sigma(\rho^0 p) = \sigma(\omega^0 p) = \tfrac{1}{2}[\sigma(\pi^+ p) + \sigma(\pi^- p)]\,,\\ &\sigma(\phi p) = [\sigma(K^- p) + \sigma(K^+ p) - \sigma(\pi^- p)] \end{aligned} \tag{4}$$

to extract $\sigma^V_{\gamma p}$ from hadronic experiments.

In Eq. (2) $\sigma^c_{\gamma p}$ consists of the high-p_t contribution from light quarks and gluons plus the contribution of charm and other heavier flavors. The essential point is that the effective mass scales involved for these are sufficiently large so that the quark-gluon coupling is small enough to allow a perturbative calculation of this component of $\sigma_{\gamma p}$ as out-

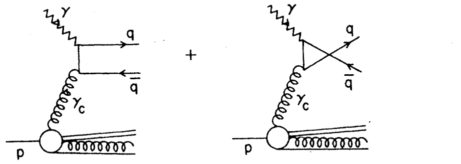

FIG. 1. Diagrams for the subprocess $\gamma+\gamma_c\rightarrow q+\bar{q}$, which is a source for high-p_t quark-antiquark jets.

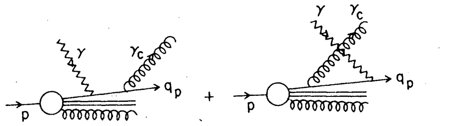

FIG. 2. Diagrams for the subprocess $\gamma+q_p\rightarrow\gamma_c+q_p$ where q_p is a quark in the initial proton. This is a source for a quark and gluon jet of high p_t.

lined below.

In the lowest order in α_c the inelastic interaction of photons with protons arises through the two basic subprocesses

$$\gamma+\gamma_c\rightarrow q+\bar{q}\,, \tag{5}$$

where γ_c is the gluon in the nucleon and q ($\bar{q}$) is *any* quark (antiquark), and

$$\gamma+q_p\rightarrow\gamma_c+q_p\,, \tag{6}$$

where q_p denotes the (predominantly light u or d) quark in the proton. These processes are shown in Figs. 1 and 2 respectively. Note that these reactions are a source for three jets, one of which is along the collision axis. For a minimum value of p_t, i.e., $p_{t\min}$ the effective threshold for these processes is $s_{0\min}$ (which is the square of the total energy of the subprocesses in their c.m. frame) $\simeq 4(p_{t\min}{}^2+m_q{}^2)$. Taking the quark-gluon coupling to be given by[14]

$$\alpha_c(Q^2)=12\pi/25\ln(Q^2/\Lambda^2)\,, \tag{7}$$

we see that for $p_t \gtrsim 1$ GeV, $\alpha_c(s_0)\lesssim 0.5$. For the case of light quarks ($m_u=m_d\sim 0.3$ GeV, $m_s\sim 0.5$ GeV) we can thus evaluate the high-p_t part of the cross section. For charm and other flavors $m_q \gtrsim 1.5$ GeV, so that their *entire* contribution via the process (5) is calculable.[15]

The cross section for these three-jet configurations is given by

$$\sigma^c_{\gamma p}(s)=\int dx\,F_{p\gamma_c}(x,s_0)\left[\sum_{q=u,d,s}\sigma^q_{\gamma\gamma_c}(s_0,p_{t\min})+\sum_{q=c,b,\ldots}\sigma^q_{\gamma\gamma_c}(s_0)\right]+\sum_{q_p=u,d,s}\int dx\,F_{pq}(x,s_0)\sigma_{\gamma q_p}(s_0,p_{t\min})\,, \tag{8}$$

where $\sigma^q_{\gamma\gamma_c}$ and $\sigma_{\gamma q_p}$ are the cross sections for the subprocesses (5) and (6) respectively, while $F_{p\gamma_c}$ and F_{pq} denote the distribution functions for the gluons and the quarks in the proton.

For purposes of numerical computations we have taken $m_u=m_d=0.3$ GeV, $m_s=0.5$ GeV, and $m_c=1.56$ GeV. In (8) the gluon coupling is taken to be a function of $s_0=xs$, as given by (7). We have used two different forms for the distribution functions of quarks and gluon in the proton: (1) the s_0-independent form of the quark distributions due to Barger and Phillips,[16] with slight modification by Buras and Gaemers[17] along with the "naive" gluon distribution $F_{p\gamma_c}(x)=3(1-x)^5/x$, and (2) the s_0-dependent distribution functions for quarks and gluons given by Glück and Reya.[18]

Figure 3 summarizes our results for the photon cross section $\sigma^c_{\gamma p}$ of Eq. (8). Dotted lines are with the s_0-independent distribution functions and solid ones for the s_0-dependent distributions. These curves include the cross section for the three-jet configurations (with $p_{t\min}=1.5$ and 1.7 GeV plus the contribution from charm. In Fig. 3 we compare these curves for $\sigma^c_{\gamma p}$ with the observed deviation

$$\Delta\sigma=\sigma_{\rm exp}-\sigma^V_{\gamma p}\,, \tag{9}$$

which is extracted from the experiment of Caldwell *et al*.[19] We see that the observed increase $\Delta\sigma$ can be accounted for by the quark-gluon contribution $\sigma^c_{\gamma p}$ for $p_{t\min}\approx 1.5$ GeV with the s_0-independent distributions and for $p_{t\min}\approx 1.7$ GeV with the s_0-dependent parametrization. The charm component of $\sigma^c_{\gamma p}$ is also shown separately in the figure. It

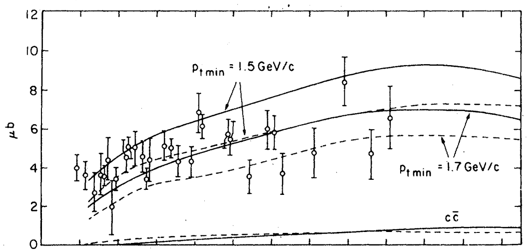

FIG. 3. Comparison of the calculated photon cross section $\sigma^c_{\gamma p}$ with the experimentally observed deviation from vector-meson (ρ, ω, ϕ only) dominance. $\sigma^c_{\gamma p}$ [see Eq. (8)] includes the cross section for the three-jet configuration of light quarks and gluons and for charm production. The component in $\sigma^c_{\gamma p}$ due to charm is also shown separately by the curves labeled *cc̄*. Dashed curves are for quark distributions without scale breaking and "naive" gluon distributions. Solid curves are for quark-gluon distributions with scale-breaking effects.

is a small fraction of $\sigma_{\gamma p}^c$ and amounts to ≤ 0.7 μb in the energy range of the photon experiment.[20] We would like to add several remarks in brief:

(1) The overall scale of the calculated photon cross section $\sigma_{\gamma p}^c$ is set by the threshold $s_{0\min} \approx 4(p_{t\min}^2 + m_q^2)$. Thus by choosing a larger value for the light quark mass one could lower $p_{t\min}$ and still obtain roughly the same numbers for the total contribution. In fact, with the effective mass for light u,d,s quarks of 1 GeV, a $p_{t\min} \approx 0.5$ GeV yields values of $\sigma_{\gamma p}^c$ that are consistent with the observed increase. We cannot resolve this ambiguity until experimental information is available on the p_t distrubution of jets in addition to the total cross-section measurements. We trust that such data will be available shortly.[11]

(2) Note from Eqs. (2) and (3) that ψ and the heavier vector mesons are treated differently in our approach. On the one hand, this is necessitated by the fact that beams of $D, F, \ldots$ mesons do not exist, so one cannot use equations analogous to (4). On the other hand, if currently popular ideas on quark-gluon interactions are correct then the VMD treatment is not necessary for the ψ, because the mass of the charm quark is sufficiently large so that its inclusive production is calculable and is therefore contained in $\sigma_{\gamma p}^c$ of Eq. (2).

(3) The calculations[3-6] based on phenomenological models such as GVMD attempting to explain the increase in photon cross section as due to $c\bar{c}$ production also need to prove that the models thus adopted are consistent with deep-inelastic lepton scattering. On the other hand, in our interpretation for the rise in γp cross section as due to the QCD graphs of Fig. 1 and Fig. 2, we do not need to separately assess their contribution to deep-inelastic scattering because effects due to gluon emission and the like are already included in the QCD (e.g., the moments) analysis of deep-inelastic scattering.

(4) Related to remark (2) is the question of quark and gluon distribution functions that we use. These are deduced from deep-inelastic scattering of virtual photons. In principle there still remains the question of what the correct distribution functions are, for use in real photon scattering, and, in particular, there is the possibility of a small error due to double counting of light quarks by inclusion of diagrams such as Fig. 1. It is because of these ambiguities that we have investigated jet production with two quite different forms for quark and gluon distribution functions. We believe that the net effect of this source of uncertainty is to make the effective $p_{t\min}$ value somewhat imprecise, to the extent already indicated. The implications of our results for experimental searches for heavier flavors, for photon-induced jets, and on the important question of the subtraction of the hadronic component of the photon[21] remain unaffected.

(5) The fact that the pointlike component of the photon contributes to the high-transverse-momentum part of the photon cross section is quite consistent with, and indeed to be expected from, the recent QCD calculations of the structure function of the photon.[21] Those calculations show that at high Q^2 (which in our work is characterized by s_0 and therefore by p_t^2 as defined earlier) the pointlike component dominates over the hadronic or the VMD part. So, while the line of demarcation between the two components is not accurately known, the fact that the photon is not just a linear combination of the vector mesons can hardly be debated. As stated in the previous paragraph, one application of the present and similar works in conjunction with experiments on photon cross section and photon-induced jets would be to yield more information so that the dual nature of the photon is better understood.

(6) Related to our discussion above [point (4)] is the question of any "primordial" transverse momentum that the partons may possess which is ignored in our treatment. That, at least partly, is justified because the distribution functions that we are using (with no primordial p_t) are constructed to fit the deep-inelastic structure functions. One could, in principle, use an altogether different representation for the structure functions with some primordial p_t. We believe that the resulting value of $p_{t\min}$ will still have an uncertainty of an extent similar to ours just because the primordial p_t is unlikely to be larger than a few hundred MeV and the value of several other parameters (such as effective quark masses, QCD coupling α_c and scale parameter, etc.) are also not known well enough. In any case our objective here was not to determine the exact value of $p_{t\min}$ but rather to point out that the increase in the photon cross section is a manifestation of the pointlike nature of the photon leading to appreciable cross section for producing high-transverse-momentum jets which can and should be experimentally studied in great detail.

(7) We have investigated only the contribution from three-jet configurations. There is obviously going to be some contribution to events with four or more jets. However, these arise from higher-order contributions in α_c and their cross sections are expected to be small in comparison to the effects calculated.

The need for experimental studies of jets in photon beams can hardly be overemphasized. It would be very illuminating to test our interpretation by (a) studies of the energy and p_t dependence of the jets, (b) study of the total photon cross section at higher energies, and (c) searches for charm and other heavier flavors.

Discussions with M. Bander and G. Shaw are gratefully acknowledged. One of us (A.S.) would also like to thank R. Morrison and A. Kernan for useful discussions. This research was supported in part by the National Science Foundation.

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