TWO-PHOTON PROCESSES IN THE PARTON MODEL

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We study here some two-photon processes in colliding $e^{\pm}e^{-}$ beam reactions, with the aim of testing the parton model. The parton contributions should dominate in certain well defined kinematical limits, and provide an essential difference between photonic and hadronic processes.

The notion that a scaling behavior should hold for the structure functions of deep inelastic electron-nucleon scattering appears to be substantiated by experiment [1]. This development has led to the suggestion that virtual photons couple locally to elementary charged constituents of the nucleon (partons [2]). Since there are other possible explanations of scaling behavior in eN scattering, it is of interest to test the physical idea of the parton model as distinct from other possible models. If the photon couples in a pointlike fashion to constituents of the hadrons, in addition to the familiar vector meson coupling to the hadron as a whole, then one might expect evidence of such a coupling to survive at various places in photon reactions - including those with real photons [3].

In this note we wist to investigate the implications of the parton model in inelastic two-photon processes involving real (γ) and virtual (γ^*) photons: $\gamma^* \to \gamma$ + hadrons, $\gamma^* + \gamma \to$ hadrons and $\gamma + \gamma \to$ hadrons, where the photons are generated in colliding electron-positron beam reactions (fig. 1) ‡. With the aim of testing the parton model, we want to take seriously the idea that the electromagnetic current couples to pointlike charged constituents of hadrons. We shall have to introduce a mass parameter for the partons and our results will end up depending on the logarithm of this parameter in the reactions just mentioned. The principal speculative element here, besides our taking the parton model itself seriously, lies in the appearance of this parameter. We can formulate our proposal as a test of the idea that these constituents move at least locally with small mass. If the expectations following from this supposition turn our to be falsified experimentally, then one would presumably either have to regard any constituents as heavy, or deprive the familar parton model of a simple physical interpretation.

We commence with an account of the parton model expectations for e^+e^- annihilation We assume that the elementary interaction is the creation of a parton-antiparton pair [5]. We expect a cross section $\sigma(e^+e^- \to$ hadrons) $= R\ \sigma(e^+e^- \to \mu^+\mu^-)$; with free spin 1/2 partons we have further $R = \Sigma e_i^2$ with parton charges e_i. The semi-inclusive reaction $e^+e^- \to$ hadron + anything should show a scaling behavior in the variable $x = 2E_{\mathrm{hadron}}/\sqrt{q^2}$ where

‡ The related processes $\gamma^* \to \gamma^*$ + hadrons and $\gamma^* + \gamma^* \to$ hadrons and their connection to the parton model have been discussed in ref. [4].

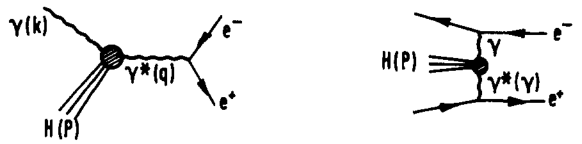

Fig. 1. The processes $e^+e^- \to \gamma^*(q) \to \gamma(k)$ + hadrons and $\gamma + \gamma^* \to$ hadrons, $\gamma + \gamma \to$ hadrons.

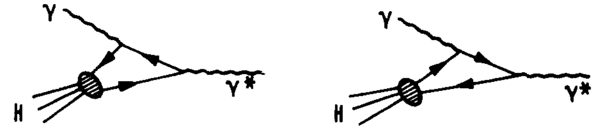

Fig. 2. $\gamma^* \to \gamma$ + hadrons. The solid lines are fermion partons

$0 < x < 1$; that is, the longitudinal and transverse structure functions $W_L(x, q^2)$ and $W_T(x, q^2)$ should be functions of x alone. In addition, one anticipates $W_L \equiv 0$ for fermion constituents. A further point of direct importance in the following is that $W_{T,L}$ should vanish as $x \to 1$, presumably as a power.

If these expectations are violated experimentally, the parton model would be cast in doubt - at least so fas as e^+e^- annihilation is concerned. Let us assume here that these expectations are satisfied, and ask if one can test the basic mechanism assumed; namely, the creation of a parton-antiparton pair. If partons are fermions of low effective mass, then the creation of a pair can be followed by one member of a pair giving up all its momentum to a bremsstrahlung photon. This depends only on the pointlike coupling of photons and partons, and should lead to photons in the final state with momentum clear out to the kinematical limit at $x = E_\gamma/E \to 1$. The fate of the parton- antiparton pair after the photon emission should be essentially the same as in the annihilation reaction $e^+e^- \to$ hadrons, provided the invariant mass of the parton- antiparton pair is above the threshold value for production of multihadron states (see fig. 2 in this connection).

The cross section for $e^+e^- \to \gamma^*(q) \to \gamma(k)$ + hadrons ($C = +1$) involves the tensor [6]

$$\frac{1}{4\pi} \sum_H (2\pi)^4 \delta_4(q-k-P) \langle H(P), \gamma(k)| j_\mu |0\rangle \langle H(P), \gamma(k)| j_\nu |0\rangle^* =$$

$$= \overline{W}_1^{(\gamma)}(k\cdot q, q^2)\left[-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right] + \overline{W}_2^{(\gamma)}(k\cdot q, q^2)\left[k_\mu - \frac{k\cdot q}{q^2}q_\mu\right]\left[k_\nu - \frac{k\cdot q}{q^2}q_\nu\right] \tag{1}$$

and can be written

$$\frac{d\sigma}{dx d\Omega} = \frac{\pi\alpha^3}{s} x \{\overline{W}_T^{(\gamma)}(1+\cos^2\theta) + \overline{W}_L^{(\gamma)}(1-\cos^2\theta)\};\ \nu = k\cdot q;\ 0 \leqslant x \equiv 2\nu/q^2 \leqslant 1;\ P^2 = (1-x)q^2;\ \cos\theta = k\cdot\hat{z}/|k| \tag{2}$$

where $\overline{W}_T^{(\gamma)} \equiv \overline{W}_1^{(\gamma)}$ and $\overline{W}_L^{(\gamma)} \equiv \overline{W}_1^{(\gamma)} + (\nu^2/q^2)\overline{W}_2^{(\gamma)}$ are the transverse and longitudinal structure functions. The contribution from the diagrams of the sort shown in fig. 2 can be calculated in perturbation theory if we treat the partons as free; this is analogous to the line of reasoning which leads to $R = \Sigma e_i^2$. We will restrict ourselves here to the fermion case. Dropping the parton mass m_0 except in the relevant logarithm, we get (notice dependence on the parton charges [7])

$$\overline{W}_T^{(\gamma)}(\text{parton}) = \frac{1}{4\pi^2}\sum e_i^4 \frac{1+(1-x)^2}{x^2}\log\frac{(1-x)q^2}{m_0^2} \qquad \overline{W}_L^{(\gamma)}(\text{parton}) = \frac{1}{\pi^2}\sum e_i^4 \frac{1-x}{x^2} \tag{3}$$

It may seem surprising that $\overline{W}_L \neq 0$, although we started out with spin 1/2 partons. We would only get $\overline{W}_L = 0$ by including some kind of cutoff so as to keep the parton near its mass shell. Such a cutoff would, however, only be appropriate for hadrons and not for photons with their pointlike coupling to the partons. We see that, as might be expected on physical grounds, $\overline{W}_L(x)$ vanishes at $x=1$ but $\overline{W}_T(x, q^2)$ remains large out to the kinematical limit and, moreover, depends on x *and* q^2. Despite its origin in the parton model, this process does not show a scaling behavior like that mentioned in connection with the one photon annihilation $e^+e^- \to$ hadron + anything. The differential cross section at $\vartheta = \Sigma e_i^4 = 1$, $m_0 \sim 0.3$ GeV and $q^2 = 16$ GeV^2 is $\sim 10^{-35}$ cm^{2}sr.

So far, we have only calculated a part of the inner bremsstrahlung reaction $\gamma^* \to \gamma$ + hadrons. We have at least a further contribution due to the vector dominance model. This should be related to the process $\gamma^* \to \rho^0$ + hadrons. if we keep for simplicity only the ρ^0 part. If this vanishes as $x \to 1$, as expected in the parton model, then the parton term in eq. (3) is the *leading* contribution as $x \to 1$. It is this feature which gives our test whatever value it may have. Since far away from $x=1$ one expects interferences between parton and vector dominance terms, it should be clear that a complete description of this process may be difficult. We mention merely that if the parton model is true, then we expect an essential difference between hadronic and photonic reactions - even for timelike photons. The two are not simply related to one another by the vector dominance model [3].

We think that this bremsstrahlung reaction is an intuitively appealing test of parton model ideas. It is evident that in the parton model this process is closely related to two other scattering processes, $\gamma^*(q^2 < 0) + \gamma(k^2 = 0) \to$

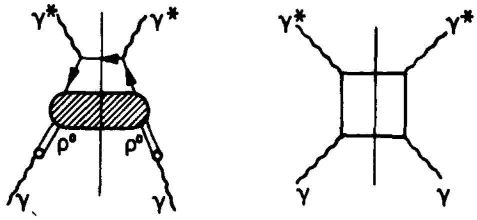

Fig. 3. Two contributions to $\gamma + \gamma^* \to$ hadrons. (a) is a VDM term and (b) the parton term which we calculate. Crossed diagrams are omitted, together with other possible contributions.

hadrons [8] and $\gamma(q^2=0) + \gamma(k^2=0) \to$ hadrons. In the former case we consider the parton term for the structure functions of an unpolarized photon in inelastic electron-photon scattering and find the contributions ($x \geqslant 1$)

$$W_{\mathrm{T}}^{(\gamma)}(\text{parton}) = \frac{1}{4\pi^2} \sum e_i^4 \, \frac{1+(x-1)^2}{x^2} \log \frac{(x-1)|q^2|}{m_0^2} \qquad W_{\mathrm{L}}^{(\gamma)}(\text{parton}) = \frac{1}{\pi^2} \sum e_i^4 \, \frac{x-1}{x^2} \tag{4}$$

We see that the parton contribution to these structure functions leads to $W_{\mathrm{L}}^{(\gamma)} \neq 0$ and to a violation of Bjorken scaling for $W_{\mathrm{T}}^{(\gamma)}$. This term is large near threshold at $x=1$, in contrast to the expectation that non-parton terms (see fig. 3) should vanish at threshold. Such terms, like the vector dominance term pictured in fig. 3, should, on account of the transverse momentum cutoff commonly assumed in the parton model for hadrons, give $W_{\mathrm{L}}^{(\gamma)} = 0$ and Bjorken scaling for $W_{\mathrm{T}}^{(\gamma)}$ in our case of spin $\frac{1}{2}$ partons. If a parton term were really present, we could conclude that deep inelastic scattering from a current is *essentially different* from deep inelastic scattering on hadrons. We emphasize again that (4) should dominate near $x \gtrsim 1$, but that the situation away from $x=1$ is alomost surely complicated. For example, the limit $x \to \infty$ may not be given by (4) but rather by scaling Regge pole contributions with $W_{\mathrm{T}} \propto x + \ldots$ rather than $W_{\mathrm{T}} \propto \log|q^2|$ as in eq. (4) [8].

We can even try to extend these considerations to on-shell photon-photon scattering. The total cross section for $\gamma + \gamma \to$ hadrons is related to the imaginary part of the forward $\gamma\gamma \to \gamma\gamma$ amplitude. We calculate the parton contribution to the helicity amplitudes $W_{\lambda_1'\lambda_2'\lambda_1\lambda_2}$ for $\gamma(\lambda_1) + \gamma(\lambda_2) \to \gamma(\lambda_1') + \gamma(\lambda_2')$ at $q^2 = k^2 = 0$ from the box diagram of fig. 3b to get

$$W_{+-+-} \approx \frac{1}{4\pi^2} \sum e_i^4 \log \frac{P^2}{m_0^2}\,; \quad W_{++++} \approx \text{const.}; \quad W_{--++} \approx \text{const.} \tag{5}$$

There are, of course, other contributions to $\gamma + \gamma \to$ hadrons besides (5). Significantly, normal Regge exchange in the t-channel with $\alpha(0) > 0$ are not expected to contribute to W_{--++} so that the leading contribution here may possibly come from the parton term [9].

Our objective has been to consider a series of linked tests of parton model ideas; these tests revolve about one term in the two-photon amplitude. We think it worthwile to check experimentally whether this term is present or not. To this end we have the following comments.

(i) $e^+e^- \to \gamma$ + hadrons has an odd charge conjugation background which can be subtracted once the e^+e^- annihilation cross section is known. The corresponding $e^+e^- \to \gamma$ + hadrons cross section can be found in ref. [6]. There is another background coming from $e^+e^- \to \pi^0$ + anything, where the π^0 has large momentum and where one photon from the $\pi^0 \to \gamma\gamma$ decay has momentum such that it lies near $x=1$. This background should be manageable for two reasons. First, $\overline{W}_{\mathrm{T,L}}^{\pi^0}$ should be suppressed near $x=1$ if the structure function vanishes there. Second, one can measure $e^+e^- \to \pi^0$ + anything and calculate the background where one photon has $x \approx 1$.

(ii) Measurement of the helicity amplitude W_{--++} in $\gamma\gamma$ scattering can be done using the reaction depicted in fig. 1 where two electrons are detected at some small but non-zero angle where q^2 and k^2 are still small, and in coincidence with one or more hadrons so as to eliminate electromagnetic background. W_{--++} is then the coefficient of a $\cos 2\phi$ term in the cross section, where ϕ is the angle between the two electron scattering planes in the $\gamma\gamma$CM frame [10]. An advantage of detecting two electrons at non-zero angles lies in the rapid decrease of multiple bremsstrahlung processes as the angle increases

(iii) Inelastic electron-photon scattering can also be studied in the reaction $e + e \to e + e +$ hadrons, but appears to be further in the future than experiments (i) and (ii). One can extend our considerations to the full set of (four) helicity amplitudes for this case if it appears warranted.

In closing, we would like to emphasize that the parton model seems to show some very distinctive features in multiphoton amplitudes. We have considered a specific model which, although it can describe only a part of the reactions we have studied, does exhibit in a clear way the distinction between photon processes and ordinary hadron processes. It has the further advantage that it is physically motivated from the basic idea of the parton model-point-like couplings of photons and partons - and can be tested experimentally in a well-defined way. Once the single photon process $e^+e^- \to$ hadrons has been studied in some detail, the next logical step is the study of the two-photon processes considered here.

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References

[1] H Kendall, Proc 1971 Inter. Symp. on Electron and photon interactions at high energies, Cornell University, Ithaca, N Y.
[2] R Feynman, (unpublished) and Cal Tech Lectures (1972),
J D. Bjorken and E.A. Paschos, Phys. Rev. 185 (1969) 1975
[3] S J Brodsky, F.E. Close and J.F. Gunion, Phys. Rev D5 (1972) 1384, and SLAC-PUB-1012 (January 1092),
S M Berman, J.D Bjorken and J.B Kogut, Phys Rev D4 (1971) 3388.
[4] D J Gross and S.B Treiman, Phys. Rev. D4 (1971) 2105,
T.F Walsh and P Zerwas, Nucl. Phys. B41 (1972) 551,
H. Terazawa, Phys. Rev. D5 (1972) 2259,
Z. Kunszt, Phys Lett. 40B (1972) 220.
[5] S.D Drell, D.J Levy and T.-M Yan, Phys. Rev. D1 (1970) 1617,
N. Cabibbo, G Parisi and M. Testa, Lett. Nuovo Cim. 4 (1970) 35.
[6] Z Kunszt, R.M Muradyan and V.M. Ter-Antonyan, Dubna E2-5347 (1970)
[7] H Suura, T F Walsh and B -L Young, Lett Nuovo Cim. 4 (1972) 505.
[8] T F Walsh, Phys Lett. 36B (1971) 121,
S J Brodsky, T. Kinoshita and H Terazawa, Phys. Rev Lett 27 (1971) 280.
[9] T F Walsh, SLAC-PUB-1111 (September 1972).
[10] C E. Carlson and W K Tung, Phys. Rev D4 (1971) 2873.