Deep Inelastic Scattering of Electrons on a Photon Target*

S. J. Brodsky
Stanford Linear Accelerator Center, Stanford, California 94305

and

Toichiro Kinoshita and Hidezumi Terazawa†
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14850
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One of the precesses which may be observed in $e^{\pm}e^{-}$ colliding-beam experiments is the deep inelastic electron-photon scattering. We examine the feasibility of such an experiment assuming an appropriate scaling limit.

The two-photon mechanism of hadron productions in e^-e^+ and e^-e^- colliding-beam experiments at high energies promises to be an important tool for studying hadronic systems of even charge conjugation state.[1-3] One of the intriguing experiments made possible by the two-photon mechanism is the inelastic electron-photon scattering,[4] i.e., the analog of the inelastic electroproduction in which the target is a *photon* rather than a nucleon. The purpose of this paper is to examine the feasibility of such an experiment. We shall first define inelastic form factors in a manner which allows us to pass to the massless-target limit. The scaling limit appropriate for a photon target is then defined. A simple estimate is made for the total hadron production cross section in the deep inelastic kinematical region. We also give an estimate of the hadron production cross section in which one of the electrons is scattered into a large angle while the second one is undetected.

Let us first consider the inelastic scattering of an electron of momentum p on a boson target B of mass M and momentum P. In parallel with the electron-proton case,[5-7] we shall define the inelastic form factors W_1 and W_2 by

$$(2\pi)^2 2P_0 \sum_n \langle P|J_\alpha(0)|n\rangle\langle n|J_\beta(0)|P\rangle(2\pi)^4\delta^4(q+P-P_n) = -\left(g_{\alpha\beta}-\frac{q_\alpha q_\beta}{q^2}\right)W_1(Q^2,\nu) + \left(P_\alpha-\frac{(P\cdot q)q_\alpha}{q^2}\right)\left(P_\beta-\frac{(P\cdot q)q_\beta}{q^2}\right)W_2(Q^2,\nu), \tag{1}$$

where J_α is the electromagnetic current of hadrons, q $(=p-p')$ the momentum transfer of the electron, $Q^2=-q^2=-(p-p')^2$, $\nu=q\cdot P$, and averaging over the target spin is assumed. Then the cross section for the process $e+B\rightarrow e+\text{anything}$ can be written as

$$\frac{d\sigma(e+B\rightarrow e+\text{anything})}{dQ^2 d\nu} = -\frac{2\pi\alpha^2}{(Q^2)^2}\left[W_2(Q^2,\nu)\left(1-y-\frac{y^2Q^2M^2}{4\nu^2}\right)+W_1(Q^2,\nu)\frac{y^2Q^2}{2\nu^2}\right], \tag{2}$$

where $P^2=M^2$ and $y=\nu/p\cdot P$. We have neglected the electron mass compared with the incident energy. We have defined W_1 and W_2 in such a way that we do not encounter any difficulty in passing to the limit $M=0$. From now on we shall regard B as a real photon. Of course in this case the rest system of the target no longer exists.

We now consider large-Q^2 and large-ν regions and assume that the Bjorken scaling limit[5] exists for the hadronic structure functions of the *photon*:

$$\lim_{\substack{\nu\rightarrow\infty\\ \omega\text{ fixed}}} W_1(Q^2,\nu)=F_1{}^\gamma(\omega),\qquad \lim_{\substack{\nu\rightarrow\infty\\ \omega\text{ fixed}}} \nu W_2(Q^2,\nu)=F_2{}^\gamma(\omega), \tag{3}$$

where $\omega=2\nu/Q^2$ $(\geq 1+m_\pi{}^2/Q^2)$, and $F_1{}^\gamma$ and $F_2{}^\gamma$ are dimensionless functions of ω and are implicitly of order α. Then for large ν and fixed ω we have the simple formula

$$\frac{d\sigma(e+\gamma\rightarrow e+\text{anything})}{dQ^2 d\nu} = -\frac{2\pi\alpha^2}{\nu(Q^2)^2}\left[F_2{}^\gamma(\omega)(1-y)+F_1{}^\gamma(\omega)\frac{y^2}{\omega}\right]. \tag{4}$$

This shows clearly that electron-photon scattering experiments in the deep inelastic kinematical region will give us information on the hadronic structure functions $F_1{}^\gamma$ and $F_2{}^\gamma$ of the photon.

In practice it is hard to find a suitable free-photon target. We shall therefore examine the feasibility of using the two-photon mechanism of e^-e^- or e^-e^+ colliding beams.[1-3] In this mechanism, both incident electrons emit virtual photons which in turn annihilate to form $C=+$ hadronic states. In order to distinguish this process from the background, we must therefore detect at least one of the scattered electrons and at the same time detect some of the produced hadrons.[8]

If we consider the situation in which the incident electron 1 of energy E is scattered into an angle θ' with energy E' while the electron 2 is scattered into a small angle $(<\theta_{\max})$, emitting an almost-real photon of energy E_γ, the corresponding cross section in the laboratory frame of colliding beams can be written in general (i.e., before the Bjorken limit is taken) as

$$\frac{d\sigma}{dE'd\cos\theta' dE_\gamma}=\frac{8\pi\alpha^2EE'}{(Q^2)^2}N(E_\gamma,\theta_{\max})\left[W_2(Q^2,\nu)(1-y)+W_1(Q^2,\nu)\frac{Q^2y^2}{2\nu^2}\right], \tag{5}$$

where the equivalent-photon method[9,10] is applied to the electron 2 and[1]

$$N(E_\gamma,\theta_{\max})=\frac{\alpha}{\pi}\left\{\frac{E^2+(E-E_\gamma)^2}{E^2}\left[\ln\left(\frac{E\theta_{\max}}{2m_e}\right)-\tfrac{1}{2}\right]+\frac{E_\gamma^2}{2E^2}\left[\ln\left(\frac{2(E-E_\gamma)}{E_\gamma}\right)+1\right]\right.$$
$$\left.+\frac{(2E-E_\gamma)^2}{2E^2}\ln\frac{2(E-E_\gamma)}{[E_\gamma^2+E(E-E_\gamma)\theta_{\max}^2]^{1/2}}\right\}. \tag{6}$$

for $m_e/E\ll\theta_{\max}\ll 1$.[11]

In the deep inelastic region, which may be defined by

$$\nu=2E_\gamma(E-E'\cos^2\tfrac{1}{2}\theta')>\nu_{\min},\quad Q^2=4EE'\sin^2\tfrac{1}{2}\theta'>Q^2_{\min}, \tag{7}$$

for an appropriate choice of $\nu_{\min}$ and $Q_{\min}^2$, the cross section (5) can be reduced to the form $[y=1-(E'/E)\cos^2\frac{1}{2}\theta']$

$$\frac{d\sigma}{dE'd\cos\theta' dE_\gamma}\simeq\frac{4\pi\alpha^2EE'N(E_\gamma,\theta_{\max})}{(Q^2)^2(E-E'\cos^2\frac{1}{2}\theta')E_\gamma}\left[F_2{}^\gamma(\omega)(1-y)+F_1{}^\gamma(\omega)\frac{y^2}{\omega}\right]. \tag{8}$$

If we do not measure the energy of the electron 2 scattered into forward angles but only specify the upper bound of its energy to be $E-E_{\min}$ so that the deep inelastic kinematics is guaranteed, it is more useful to integrate (8) over E_γ:

$$\frac{d\sigma}{dE'd\cos\theta'}\simeq\frac{4\pi\alpha EE'}{(Q^2)^2(E-E'\cos^2\frac{1}{2}\theta')}\int_{E_{\min}}^{E}\frac{dE_\gamma}{E_\gamma}N(E_\gamma,\theta_{\max})\left[F_2{}^\gamma(\omega)(1-y)+F_1{}^\gamma(\omega)\frac{y^2}{\omega}\right], \tag{9}$$

where $E_{\min}=\nu_{\min}/[2(E-E'\cos^2\frac{1}{2}\theta')]$.

In the ep case the scaling region seems to start at $\nu\sim$ several GeV^2 and $Q^2\sim 0.5$ (GeV/c)^2.[12] Thus $Q_{\min}^2$ for ep scattering is less than $\frac{1}{2}$ of the threshold value for the πp continuum. If the similar situation prevails in the ee scattering too, $Q_{\min}^2$ will be close to the threshold of a few-pion system and probably be of order 0.1 (GeV/c)^2. We may choose $\nu_{\min}\sim 1$ GeV^2 in the same analogy. Of course we do not know whether such an argument is correct: After all these are quantities to be determined by experiment.

In order to estimate the magnitude of the cross sections (8) and (9), let us assume the parton model with spin $\frac{1}{2}$ constituents. Then we have[6,7,13]

$$F_1{}^\gamma(\omega)=\tfrac{1}{2}\omega F_2{}^\gamma(\omega). \tag{10}$$

We shall further make use of the very rough estimate

$$F_2{}^\gamma(\omega)\simeq(\sigma_{\gamma p}/\sigma_{pp})F_2{}^p(\omega)\simeq\tfrac{1}{300}0.3 \tag{11}$$

based on factorization. Then, for typical values $E=2.5$ GeV, $E'=1.0$ GeV, $\theta'=15°$, $E_\gamma=0.5$ GeV, $\theta_{\max}=5.7°$, the cross section (8) becomes

$$\frac{d\sigma}{dE'd\cos\theta' dE_\gamma}\simeq 4.2\times10^{-34}\ \mathrm{cm^2/GeV^2}. \tag{12}$$

[The values of other quantities are $\nu = 1.5\ \mathrm{GeV}^2$, $Q^2 = 0.17\ (\mathrm{GeV}/c)^2$, $\omega = 18$, $y = 0.61$.] For the same values of E, E', θ', $\theta_{\max}$, and $E_{\min} = 0.5$ GeV (hence $\nu \geq 1.5\ \mathrm{GeV}^2$), we obtain from (9)

$$\frac{d\sigma}{dE'd\cos\theta'} \simeq 3.3\times 10^{-34}\ \mathrm{cm}^2/\mathrm{GeV}. \tag{13}$$

Integrating (9) over E' and $\cos\theta'$ in the deep inelastic region we obtain

$$\sigma \simeq \frac{4\alpha^3}{Q_{\min}^2}\left(\ln\frac{E\theta_{\max}}{m_e}\right)\left(\ln\frac{E}{E_{\min}}\right)\left(\ln\frac{2E^2}{\nu_{\min}}\right)F_2^{\gamma} \simeq 5.4\times 10^{-35}\ \mathrm{cm}^2 \tag{14}$$

for $E = 2.5$ GeV, $\nu_{\min} = 1.5\ \mathrm{GeV}^2$, $E_{\min} \sim 0.5$ GeV, and $Q_{\min} = 0.17\ (\mathrm{GeV}/c)^2$. From these examples we see that the deep inelastic scattering on a photon target will provide a practical and exciting opportunity for the new high-energy, high-luminosity colliding-beam facility now under construction.

If we do not detect the electron 2 at all, it is no longer possible to maintain the condition of deep inelasticity. Nevertheless this case may be of some experimental interest because the cross section then is larger and easier to measure, and will serve as a preliminary test of deep inelastic measurements. Note that typical colliding-beam experiments will be carried out under the condition that particles produced in all directions except for some narrow cones in the beam direction are detected. Thus detection of one of the electrons scattered into a large angle does not require any substantial modification of detectors and will therefore be feasible in the near future. On the other hand, there is no theory at present which applies to this case. If we pick up only the contribution from the deep inelastic region (i.e., keep the restriction $E_\gamma > E_{\min}$ but let $\theta_{\max}$ be of order 1), the result gives us a lower bound. Thus, if the second electron is not detected at all, the cross section will satisfy for $E = 2.5$ GeV

$$\sigma \gtrsim 7.4\times 10^{-35}\ \mathrm{cm}^2. \tag{15}$$

Finally, we give an additional argument to support our assumption (11). If we follow the Bjorken-Paschos interpretation of the structure function,[6] we anticipate the ω dependence of $F_2^{\gamma}(\omega)$ to be similar to that of $F_2^{p}(\omega)$. However, the magnitude of $F_2^{\gamma}(\omega)$ will depend on two factors: (1) the probability of finding the hadronic state in the target photon which is of the order of e^2/g^2 if we adopt the vector-dominance model with the universal coupling constant g ($g^2/4\pi \simeq 2.0$); (2) the factor depending upon the structure of the hadronic state of the photon which is different from that of the nucleon. If we take the quark model in (2), we find the sum rule of Bjorken-Paschos-Drell-Levy-Yan type[6,7]

$$\int_0^1 F_2^{\gamma}(\omega)d(\omega^{-1}) \simeq \tfrac{2}{9}e^2/g^2 \simeq 8\times 10^{-4} \tag{16}$$

which is consistent with (11).

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Note added in proof.—After completing this work we received a preprint by T. F. Walsh [DESY Report No. 71/15, 1971 (to be published)] on the same subject as ours.

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†Permanent address: The Rockefeller University, New York, N. Y. 10021.

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since the produced hadrons are to be detected simultaneously, no serious background problem arises from Bhabha scattering and its radiative corrections. The background due to hadrons produced in $C = -$ states by the bremsstrahlung of virtual photons in e^+e^- collisions appears to be strongly suppressed in the deep inelastic region.

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Experimental Evidence for a High-Mass Vector Meson*

A. Benvenuti, D. Cline, R. Rutz, D. D. Reeder, and V. R. Scherer
Physics Department, University of Wisconsin, Madison, Wisconsin 53706
(Received 10 June 1971)

We have measured the cross section for the reaction $\bar{p}p \to K_S^0 K_L^0$ from 100–800 MeV/c. A significant enhancement in the cross section is observed at a mean momentum of 600 MeV/c. A Legendre-polynomial analysis of the angular distributions also shows an enhancement in the A_2 coefficient in the same momentum range. A plausible explanation of the data indicates a new meson state $\rho(1970)$ with a mass $M = 1968$ MeV, width $\Gamma = 35$ MeV, and $J^{PC} = 1^{--}$.

Recently many theories and phenomenological analyses have suggested the existence of additional vector-meson states.[1,2] However, no conclusive evidence for such states has been obtained from any production experiment to date.[3] Presumably if these states were formed in production experiments they would be masked by high-spin states. In contrast, formation experiments with the $\bar{p}p$ system might be sensitive to the existence of low-spin states since high-spin states should be relatively suppressed by the centrifigal barrier at low antiproton momentum. In addition the selection of particular annihilation final states can enhance the signal to noise for selected mesonic quantum members. Annihilation states with $K^0\bar{K}^0$ pairs are particularly useful for isolating selected charge-conjugation states of the $\bar{p}p$ system. In particular the $K_L^0 K_S^0$ final state is a pure $C = -1$ state as are vector mesons. In this note we report a study of the cross section and angular distribution for the annihilation process in the $K_L^0 K_S^0$ final state below 800 MeV/c antiproton momentum. We present evidence for the existence of a new high-mass vector meson.

The data reported in this note were obtained from a 250 000 picture exposure of the Brookhaven National Laboratory 30-in. bubble chamber to a separated antiproton beam at the alternating-gradient synchrotron. The beam momentum was varied so that the momentum range of 800–400 MeV/c was covered with approximate uniform flux. The momentum range of 100–400 MeV/c was covered with a considerably smaller flux. The primary purpose of the exposure was to search for s-channel structure in low-energy $\bar{p}p$ scattering and several reports on this subject have already appeared.[4-6] Each picture contained approximately ten antiprotons giving a total of 2.5×10^6 antiprotons in the exposure.

The film has been scanned for all events with one or two pointing V's and a zero-prong star. These events fall into the categories

$$\bar{p}p \to K_S^0 + K_S^0 + n(\pi^0), \quad (1)$$

$$\bar{p}p \to K_S^0 + (K^0)_m + n(\pi^0), \quad (2)$$

where $(K^0)_m$ represents either a K_L^0 meson which leaves the bubble chamber or a K_S^0 with a neutral decay and K_S^0 represents a visible $\pi^+\pi^-$, K_S^0 decay. All events of type 1 were tested for the hypothesis

$$\bar{p}p \to K_S^0 + K_S^0, \quad (3)$$

and only one event in this category was observed in the entire experiment. The significance of the low rate for this process is discussed in another place.[7] For Reaction (2) a missing-mass spectrum recoiling against the K_S^0 was constructed and showed a very clean bump at the position of the K^0 mass. The mass squared and half-