Commission.

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[1]Single-photon results are discussed by D. O. Caldwell *et al.*, following Letter [Phys. Rev. Lett. 33, 868 (1974)].

[2]The most comprehensive reference on the CIM is R. Blankenbecler and S. J. Brodsky, SLAC Report No. SLAC-PUB-1430, 1974 (to be published). See also references referred to therein.

[3]Manufactured by Ohara Optical Glass Mfg. Co., Ltd.

[4]Manufactured by Schott Optical Glass, Inc.

[5]For shower properties, see two unpublished DESY reports by U. Völkel (1965).

[6]H. Davies, H. A. Bethe, and L. C. Maximon, Phys. Rev. 93, 788 (1954).

[7]These data were collected by our group with the aid of the physicists of Stanford Linear Accelerator Center experiment 66, and reduced with the help of D. Sherden.

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Measurements of Inelastic Compton Scattering*

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We have measured inelastic Compton scattering of 21-GeV bremsstrahlung photons on protons, for p_T above 1 GeV/c. The yield of photons after subtracting π^0 and η decay contributions appears to be nonhadronic and is greater than parton-model predictions for integer-charged partons. The constituent-interchange model provides a possible explanation.

Shortly after the first deep inelastic electron-proton scattering experiments, Bjorken and Paschos[1] suggested that inelastic Compton scattering might also probe the proton's structure. In their simple parton model, inelastic Compton scattering at sufficiently large four-momentum transfer (t) is the incoherent sum of processes in which the photon is elastically scattered by a pointlike parton of charge Q_i. The inelastic Compton cross section thus measures $\langle \sum_i Q_i^4 \rangle$, where the sum is over all partons in a configuration, and the average is over all contributing configurations.

Inelastic electron scattering in such a model measures $\langle \sum_i Q_i^2 \rangle$. Bjorken and Paschos predicted that (for spin-0 or spin-$\frac{1}{2}$ partons)

$$\left(\frac{d^2\sigma}{dE\,d\Omega}\right)_{\gamma p} = \frac{(k-E)^2}{kE}\left(\frac{d^2\sigma}{dE\,d\Omega}\right)_{ep} \frac{\langle \sum_i Q_i^4 \rangle}{\langle \sum_i Q_i^2 \rangle}, \qquad (1)$$

where k and E are the incident and scattered energies and the electron scattering cross section is evaluated for $q^2 = t$.[1] The charge-ratio factor should depend only upon $\omega = 2M(k-E)/(-t)$. If the partons are of charges 1 and 0, the factor is just unity (constant). For any quark-parton model in which the nucleon consists of three quarks and a $q\bar{q}$ sea, the ratio must lie[2] between $\frac{1}{9}$ and $\frac{4}{9}$ for all ω; the upper limit of $\frac{4}{9}$ is attained for p-quark dominance. Hence, it was suggested, inelastic Compton scattering measurements can distinguish between integrally charged and fractionally charged partons.

In an experiment at the Stanford Linear Accelerator Center, we have measured the yields of single photons produced from a 21-GeV bremsstrahlung beam striking a proton target. We simultaneously measured the yields of π^0 mesons and (with limited statistics) η mesons, by detecting two-photon coincidences.[3] Their contributions to the photon yields can therefore be subtracted, leaving an inelastic Compton scattering cross section.

Two related experiments have been reported. One was our preliminary look at inelastic Compton scattering in which only single photons were detected.[4] After the π^0 contribution was subtracted under the assumption that π^0's and π^+'s were produced equally, the remaining photon yield was too large for even charge-1 partons. The second experiment measured the deep inelastic photoproduction of low-mass muon pairs from a Be target.[5] The yield (integrated over a large kinematic region) was about ten times that expected from Bethe-Heitler and inelastic Compton processes in the simple parton model.

Our apparatus, experimental procedure, and data reduction scheme have been described previously.[3] The single-photon yields were corrected for empty-target rates (− 6%); beam attenuation in the target (+1%); pileup (− 5 to − 10% for stack 1 and − 10 to − 21% for stack 2); and charged hadron contamination (− 2% and − 9% for the two stacks, as determined from data with lead absorbers in front). No correction was made for electrons, because measurements[6] indicate that they could not account for more than 1% of our photon yields. The cross section for the major background process, π^0 production, was measured simultaneously by detecting two-photon events.[3] We were thus able to compute accurately (using a Monte Carlo program) the contribution of π^0's to our photon yields, and subtract this contribution in apparent E versus p_T bins. The dominant sources of systematic uncertainty were the pileup correction (assigned an uncertainty of approximately half the correction) and uncertainties in the energy scale.[3] Systematic uncertainties were mostly applied to the π^0 and single-photon yields before subtraction, but some were applied as overall normalization uncertainties.

Monte Carlo fits[3] to the π^0-subtracted data were then used to determine an "excess-photon" cross section for each of the four independently analyzed data points (two stacks of lead glass at two angles). In their regions of overlap, results were consistent within systematic uncertainties. Finally, these cross sections (and their systematic uncertainties) were averaged, to obtain the results in Fig. 1. (Only points at alternate independent values of p_T are shown.) This cross section does not fall as rapidly with p_T as does the π^0 contribution. To demonstrate this, we have sketched in Fig. 2 the average fraction of the *total* photon yield due to π^0's as a function of p_T.

We have found[3] $(\eta \to 2\gamma)/\pi^0 = 0.20 \pm 0.065$. We have assumed this ratio to be independent of p_T and E, an assumption consistent both with our data and with theoretical expectations.[7] A Monte Carlo calculation indicates that the contribution of η's to our photon yield at a given energy is increased by 1.3 relative to that of π^0's. Therefore the net contribution of $\eta \to 2\gamma$ decays to the single-γ yield has been taken as a constant 0.26 ± 0.08 times the π^0 contribution. This is also sketched in Fig. 2.

For each p_T value in Fig. 1, a smooth curve has been drawn through the data, and an η contribution subtracted. The resulting excess photon cross sections (with *both* π^0's and η's subtracted) are given by the solid curves in Fig. 3, shown with systematic uncertainties. (Up to 65% of the latter could be E dependent, but aside from the η subtraction there are no significant p_T-dependent systematic uncertainties at constant E.) The short-dashed curves are the predictions of the Bjorken-Paschos model[1] for *integer*-charged partons. These were obtained by integrating Eq. (1) over a bremsstrahlung spectrum,[8] using a parametrization for the inelastic electron scattering cross section.[9] Recall that for *quark* partons the predictions lie at least a factor of $\frac{4}{9}$ lower still.

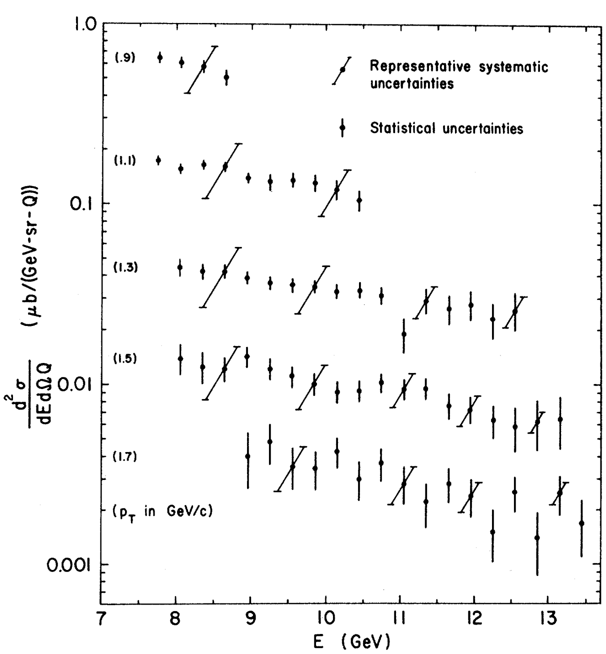

FIG. 1. Inclusive cross section per equivalent quantum for photon production from 21-GeV bremsstrahlung, after subtraction of photons from π^0 decays.

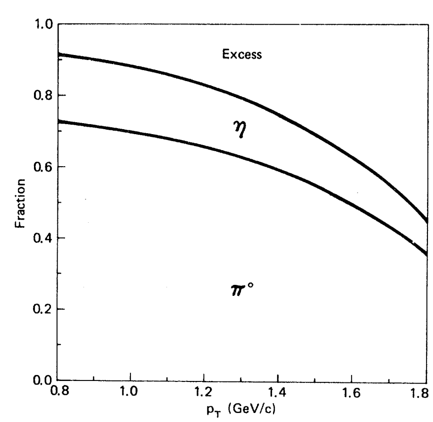

FIG. 2. Sketch of the proportions of single-photon yields due to π^0 decay, $\eta \to 2\gamma$ decay, and the remainder. (See text for assumptions.) This is only approximate; local fluctuations and a small E dependence for constant p_T have been ignored.

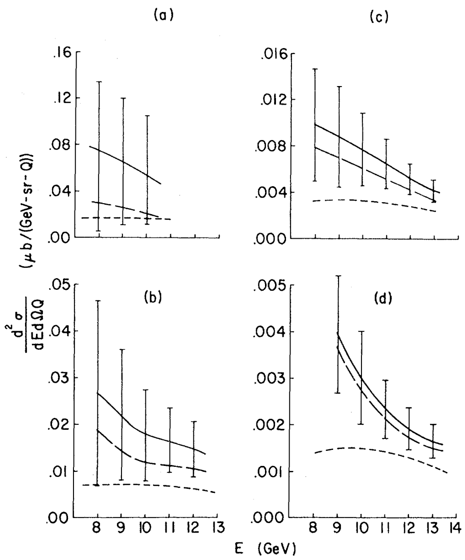

FIG. 3. Excess-photon (inelastic Compton) cross sections for four values of p_T: (a) 1.1 GeV/c, (b) 1.3 GeV/c, (c) 1.5 GeV/c, and (d) 1.7 GeV/c. The solid curves (with systematic error bars) show cross sections after subtraction of π^0 and η contributions. The long-dashed curves assume that all low-p_T photons are hadronic (see text). The short-dashed curves are parton-model predictions (Ref. 1) for integer-charged partons.

It is possible that we have ignored some additional hadronic source of photons (not mediated by π^0's). Decays into three or more particles are very unlikely to produce many high-energy photons. The only plausible potential source is $\omega \to \pi^0\gamma$. If ω and π^0 production were identical, the odd-photon contribution of $\omega \to \pi^0\gamma$ decays would be about 7% of the number of photons from π^0 decays. (There exist preliminary data on inclusive ρ^0 photoproduction at low p_T which indicate a cross section at $p_T \approx 0.8$ GeV/c comparable to that for π^0's.[10] Inclusive pp measurements have found that ω and ρ^0 rates are approximately the same.[11] We have seen no evidence for $\omega \to \pi^0\gamma$ in our two-stack coincidence data,[3] but because of our small acceptance for such events we can only set an upper limit on ω production of 5 times π^0 production.) For *any* type of neglected hadronic contribution, we can assume, as for the η's, that such a single-photon yield is proportional to that from π^0's. Even if *all* photons at our lowest p_T were due to such sources, still, because the single-γ yield and these π^0-like yields depend differently on p_T, most of the nonhadronic photon excess would remain at our higher p_T values —see the long-dashed curves in Fig. 3.

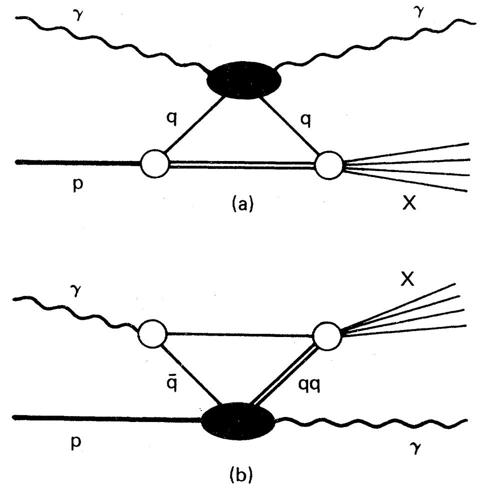

FIG. 4. CIM diagrams for inelastic Compton scattering. (See text and Ref. 7.)

It seems most likely that we are, in fact, seeing an inelastic Compton-scattering cross section larger than expected from a simple parton model with charges ≤ 1. Moreover, it decreases more rapidly with both p_T and E than does the Bjorken-Paschos form. A suggestion as to its origin is provided by the constituent interchange model (CIM).[7] The important CIM contributions are illustrated in Fig. 4, where the shaded ovals represent high-p_T irreducible subprocesses. For small values of $\epsilon \approx 1-(p/p_{\max})_{\text{c.m.}}$, a single such term contributes

$$E d^3\sigma/dp^3 \propto \epsilon^b/(p_T^2+\mu^2)^a. \tag{2}$$

For Fig. 4(a), $a=2$ (or slightly larger if the photon sometimes behaves like a vector meson) and $b=3$; for Fig. 4(b), $a=5$ and $b=0$ to 1. Figure 4(a) is just the Bjorken-Paschos process. However, the CIM predicts that the inverted process of Fig. 4(b), which essentially measures photon structure rather than proton structure, can also occur. A CIM fit to our π^0 photoproduction data[3] showed that in our kinematic region a term analogous to Fig. 4(b) was most important. If this application of the CIM is valid, the same might well occur for inelastic Compton scattering.

As a crude test of this idea we have compared our excess-photon results (the solid curves of Fig. 3) with the predictions of Eq. (2) integrated over a bremsstrahlung spectrum. For $b \approx 0.5$ (certainly $b \lesssim 1.0$ is necessary) and $\mu^2 = 0.8$ (GeV/c^2)^2, $a \approx 4.5$ is a best "fit." Thus our results seem consistent with Fig. 4(b) alone, but our large uncertainties permit a contribution from

Fig. 4(a). The Bjorken-Paschos process alone is inadequate to explain our results. If both our inelastic Compton and inclusive π^0 cross sections are due to photon-structure terms such as Fig. 4(b), we would expect their values of b to be similar. This is indeed the case; however, the ratio of γ to π^0 cross sections (typically ≈ 0.1 rather than α) is perhaps too large to be explained by this mechanism.

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