Inclusive Production of Direct Photons in 200-GeV/c Collisions

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The authors have measured the inclusive production of direct photons in the transverse momentum (p_T) range 2.1– 5.0 GeV/c in 200-GeV/c collisions of protons and π^+ mesons on a carbon target. A significant yield of direct photons was observed for $p_T > 2.5$ GeV/c. The invariant cross section for direct-photon production, when compared with measurements from the CERN intersecting storage rings, can be expressed in terms of p_T and $x_T = 2p_T\sqrt{s}$ as $(42 \pm 14)(1 - x_T)^{8.1 \pm 1.0} p_T^{-6.6 \pm 0.3}$ μb/GeV^2 for the c.m. energy range from $\sqrt{s} = 19.4$ to 63 GeV, and for the x_T range from 0.2 to 0.5.

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Several experiments have reported evidence for the production of direct photons at large p_T in hadronic collisions.[1,2] Experimental interest in this process continues,[3] despite the fact that background from the decay of π^0 and η mesons make such measurements technically rather challenging. The most compelling reason for the continued interest in direct photons is that the subprocess which is expected to dominate the $pN \to \gamma X$ reaction at large p_T is related to the elementary quantum chromodynamic (QCD) analog of Compton scattering [Fig. 1(a)].[4] Replacing the final-state gluon by a real photon [Fig. 1(b)] eliminates the ambiguities normally associated with triggering an experiment on a jet of hadronic fragments from a scattered gluon. Consequently, an analysis of direct-photon production can, in principle, provide a clean way to study this and other basic QCD scattering processes.

We report here on a measurement at Fermilab of inclusive direct-photon production near 90° in the center-of-mass system for 200-GeV/c collisions of protons and π^+ mesons on a carbon target. The apparatus and trigger were described in the preceding Letter, where we presented the inclusive cross sections for π^0 and η mesons.[5] Similar procedures were followed in the extraction of the direct-photon process. The lack of a mass constraint for the single photon, however, necessitated the imposition of cuts to reduce hadronic contamination and background from beam-halo–induced events. Three criteria were applied to the highest-energy photon in each event: (1) The energy deposited in the first 12 radiation lengths of the photon detector had to be > 50% of the total shower energy. (2) The photon signal had to occur within ± 25 nsec of the interaction time. (3) The direction of the photon shower, as determined from the signals in the front and back of the photon detector, had to point to within ± 5° of the target. These criteria eliminated essentially all background from events originating from the halo region of the beam.[6]

The decays of π^0 and η mesons into two photons form the dominant source of background to the direct-photon signal. In Fig. 2 we display the energy asymmetry distributions for the $\gamma\gamma$ decays of these mesons, and the predictions of a Monte

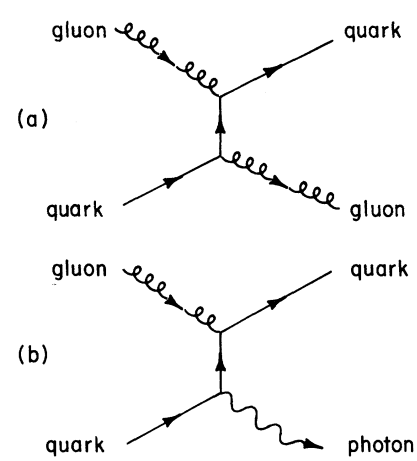

FIG. 1. The QCD analogues of Compton scattering.

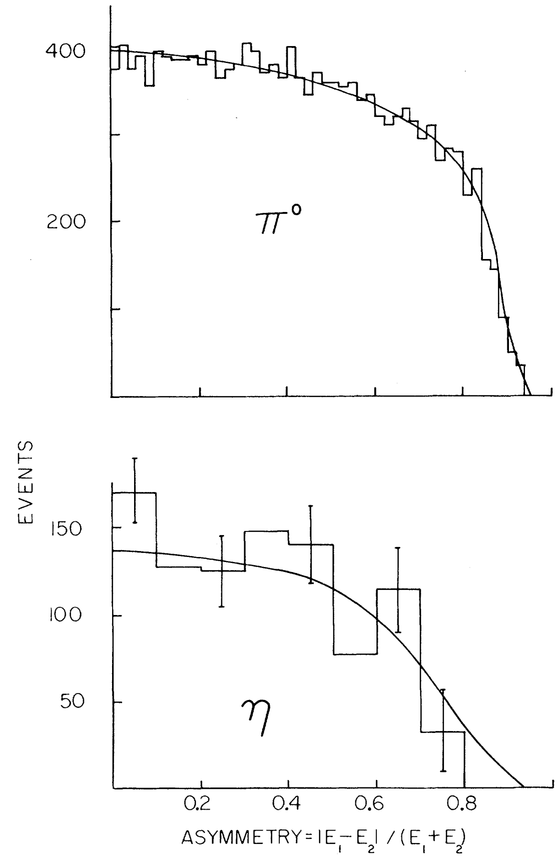

FIG. 2. Energy asymmetry distributions (background subtracted) for π^0 and η mesons. The curves are the predictions of a Monte Carlo simulation of the detector's response to the inclusive yields.

Carlo program which simulates the response of the detector. These distributions would have been isotropic if there were no decay losses. The acceptance is excellent for low asymmetries.[5] At high asymmetries, the deterioration in the acceptance is reproduced accurately by the Monte Carlo calculation. It can be concluded, therefore, that the Monte Carlo program should also be reliable for calculating the background to any direct-photon signal resulting from the losses of asymmetric π^0 and η decays. Additional simulation studies of the detector and visual inspection of the direct-photon candidates have shown that, for our range of p_T values, the loss of π^0's due to the coalescence of photons in symmetric decays is negligible.[7]

A large p_T photon was classified as either a "single" or a "paired" photon, depending on whether that photon, when combined with every other photon in the event, yielded a $\gamma\gamma$ mass that was within 25 MeV of the π^0 mass or within 50 MeV of the η mass. The single photons were then corrected for loss of signal due to random pairing of photons that fell in the π^0 or η mass range. Corrections were also applied for acceptance and trigger efficiency. The ratio of single photons to the inclusive π^0 yield is shown for proton and π^+ beams in Figs. 3(a) and 3(b), respectively. The data have been integrated over c.m. rapidities between -0.75 and $+0.2$. Also shown are the background contributions to the ratio expected from the undetected π^0 and η decays, ω^0 and η' decays,

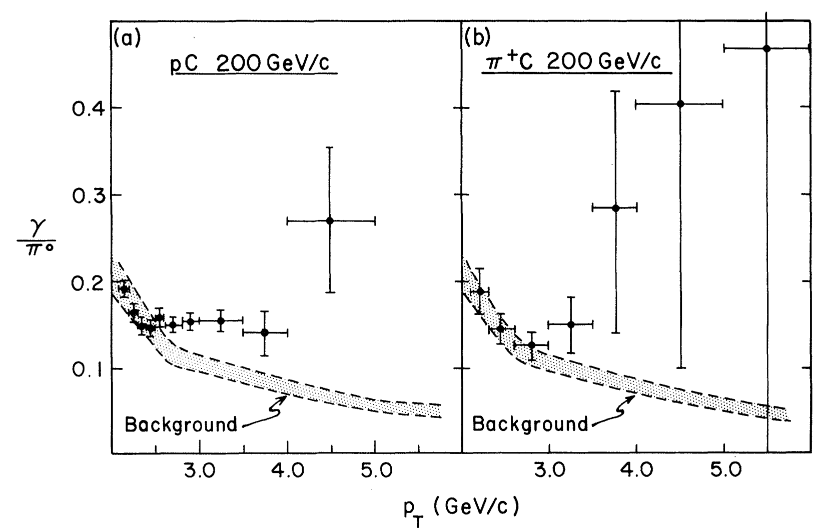

FIG. 3. Inclusive cross section for single photons divided by the π^0 inclusive cross section. The curves labeled "background" represent upper and lower limits on the background contributions to the ratio expected on the basis of a Monte Carlo calculation.

and hadron contamination. Typically, the π^0 and η decays constitute, respectively, 70% and 15% of this background. Below a p_T of 2.5 GeV/c the data are consistent with contributions expected from the background. For $p_T > 2.5$ GeV/c there is a clear γ excess over that expected from the background.

We have subtracted the background to the γ/π^0 ratio and computed cross sections for direct-photon production; the results are given in Table I. We wish to emphasize that these are inclusive measurements; no restrictions have been placed on the associated event structure. In fact, most of our single-photon and π^0 triggers above a p_T of 2.5 GeV/c consist of isolated showers with little if any additional electromagnetic activity within the acceptance region of the photon detector.

Our results are in reasonable agreement with a previous measurement of the γ/π^0 ratio at Fermilab (Baltrusaitis *et al.*[1]) of $\gamma/\pi = 0.05-0.09$ in $p\mathrm{Be} \to \gamma X$, for $p_T > 3$ GeV/c. However, at smaller values of transverse momentum ($p_T < 2.5$ GeV/c) we obtain an upper limit for γ/π^0 of 0.02; this result is well below that of the previous experiment. Our results are more consistent with those obtained at the CERN intersecting storage rings (ISR), where measurements of direct photons[2] and of low-mass virtual photons (e^+e^- pairs)[8] indicate several-percent upper limits for the γ/π^0 ratio in the p_T range of 2–3 GeV/c, and a subsequent rapid rise of that ratio with increasing p_T. The measurements of Diakonou *et al.*[2] in the p_T range of 3–4 GeV/c at $\sqrt{s} = 31$ GeV are consistent with the value of $\gamma/\pi^0 = 0.06 \pm 0.02$ that we find for $\sqrt{s} = 19.4$ GeV.

To investigate the scaling behavior of inclusive photon production with energy we have performed a fit to our data and to the measurements from the ISR that have the most reliable absolute normalization.[9] Using the form $C(1-x_T)^N P_T^{-M}$, where C is a normalization factor, we obtain $N = 8.1 \pm 1.0$, $M = 6.6 \pm 0.3$, and $C = (4.2 \pm 1.4) \times 10^{-29}$ cm^2/GeV^2. Effects from uncertainty in the relative normalization of the two experiments have been included in the errors.

Theoretical estimates[4] for γ/π^0 are about a factor of 2 below our results. This is reminiscent of a similar discrepancy in the $\mu^+\mu^-$ yield in Drell-Yan production. Thus it appears that theoretical difficulties remain in explaining the absolute yield of single photons.[10]

We note that the results for the γ/π^0 ratio are similar in both the proton and π^+ data. In view of the predicted dominance of the u-quark Compton process for photons in this range of p_T, only small differences in the ratio would have been expected.

In conclusion, we have observed a clear signal for direct-photon production in both pC and π^+C collisions for $p_T > 2.5$ GeV/c. The ratio of γ/π^0 is larger than 0.10 beyond a p_T of 4.0 GeV/c, and less than 0.02 for $p_T < 2.5$ GeV/c. The γ/π^0 ratio at fixed p_T appears to be nearly energy independent between $\sqrt{s} = 19.4$ GeV and $\sqrt{s} = 63$ GeV. Finally, the inclusive photon yield has a p_T dependence that is close to the form observed for production of constituent jets at the ISR,[11] as would be expected on the basis of the kind of diagrams shown in Fig. 1.

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TABLE I. Background-subtracted γ/π^0 ratios and the invariant cross sections for direct-photon production at 90° in the center-of-mass system for 200-GeV/c collisions on carbon. The calculations of the cross section per nucleon assume a linear dependence on A for direct-photon production.

Reaction	p_T (GeV/c)	γ/π^0 (%)	$E\,d\sigma/d^3p$ (cm^2/GeV^2 nucleon)
$p\mathrm{C} \to \gamma + x$	2.25	<2.2	$< 1.9 \times 10^{-32}$
	2.45	<2.0	$< 7.6 \times 10^{-33}$
	2.55	1.0 ± 1.9	$(2.4 \pm 4.7) \times 10^{-33}$
	2.70	3.4 ± 1.7	$(4.6 \pm 2.3) \times 10^{-33}$
	2.90	4.3 ± 1.8	$(2.7 \pm 1.1) \times 10^{-33}$
	3.25	5.6 ± 1.8	$(1.1 \pm 0.3) \times 10^{-33}$
	3.75	5.6 ± 2.9	$(1.6 \pm 0.8) \times 10^{-34}$
	4.50	20.8 ± 8.5	$(5.8 \pm 2.5) \times 10^{-35}$
$\pi^+\mathrm{C} \to \gamma + x$	2.20	<3.3	$< 2.5 \times 10^{-32}$
	2.45	<2.4	$< 6.4 \times 10^{-33}$
	2.80	1.2 ± 2.2	$(1.2 \pm 2.2) \times 10^{-33}$
	3.25	5.0 ± 3.5	$(1.0 \pm 0.7) \times 10^{-33}$
	3.75	20 ± 14	$(4.3 \pm 2.9) \times 10^{-34}$
	4.50	34 ± 30	$(7.8 \pm 6.7) \times 10^{-35}$
	5.50	42 ± 47	$(3.3 \pm 3.7) \times 10^{-35}$

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[6]C. Nelson *et al.*, to be published; and J. Biel *et al.*, in *Proceedings of the Seventeenth Rencontre de Moriond, Les Arcs, France, 1982,* edited by J. Trân Thanh Vân (Editions Frontières, Gif-sur-Yvette, 1982).

[7]We should point out that, because we did not have an analyzing magnet in this experiment, the $e^+e^-\gamma$ Dalitz mode of the π^0 appeared identical to the $\gamma\gamma$ mode in the liquid-argon calorimeter. That is, the two electrons essentially merged into one shower, and these decays were not lost from the π^0 sample.

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[9]E. Anassontzis *et al.*, Z. Phys. C 13, 277 (1982). These are essentially the results of the experiment of Diakonou *et al.*, Ref. 2, corrected by a factor of ~1.4 to correct the measurements to inclusive yields. Also see V. Burkert's study of the scaling properties of direct-photon production, in Proceedings of the Eighteenth Rencontre de Moriond, Les Arcs, France, 1983, edited by J. Trân Thanh Vân (to be published); and J. Huston, in Proceedings of the Colloquium on Multiparticle Dynamics, Lake Tahoe, 1983, edited by J. Gunion (to be published).

[10] We thank A. Contogouris and J. F. Owens for helpful discussions of the phenomenology.

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