Inclusive Photon Production from $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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We report a measurement of the inclusive production of low-energy photons from $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. A NaI calorimeter located near $\eta = 0$ was used to measure the photon transverse momentum spectrum over the range $30 \leq p_t \leq 5000$ MeV/c. The data are compared to the photon production expected from known particle decays in an attempt to isolate a low-energy direct photon signal. We find no evidence for excess photons above those expected from hadron decays and place an upper limit of 16% (90% C.L.) on any excess direct photons in the p_t range from 30 to 100 MeV/c.

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In this Letter we present the first measurement of inclusive photon production from $p\bar{p}$ collisions at the Tevatron collider. The data are used to search for low-energy (<100 MeV) direct photon production by comparing the measured inclusive photon spectrum to that expected from photons coming from the decay of hadrons. Parton-level sources of direct photons are $q\bar{q}$ annihilation and qg Compton scattering [1]. In addition, soft photons can be produced directly from coherent hadronic inner bremsstrahlung [2] and, if a quark-gluon plasma (QGP) is formed, from the bremsstrahlung of quarks accelerating in the color field confining the plasma [3].

Evidence for anomalous soft photon sources has been reported previously. A large excess of photons with $p_t < 60$ MeV/c above those expected from hadronic inner bremsstrahlung was measured in an experiment studying K^+p collisions at $\sqrt{s} = 11.5$ GeV [4]. Another experiment studying K^+p and π^+p collisions at $\sqrt{s} = 21.7$ GeV has reported an excess of centrally produced, low-p_t (<40 MeV/c) photons [5] which is claimed to be consistent with a cold QGP model proposed by Van Hove [6]. Other experiments have found no evidence of anomalous photon signals [7]; in particular, a careful study of low-energy photon production from 450 GeV/c p-Be collisions finds no evidence for excess photons down to a p_t of a few MeV/c [8]. The measurement reported here extends the search for direct low-energy photon signals to 1.8 TeV, the highest center-of-mass energy currently available, and thus provides a unique test for the appearance of anomalous photons with increasing $\sqrt{s}$.

The data come from the E735 Tevatron experiment, designed to measure simultaneously many of the possible QGP signatures. The E735 detectors which surrounded the beam line covered 2π in azimuth and $|\eta| \leq 3.25$ ($|\eta| \leq 4.5$ with trigger hodoscopes) in pseudorapidity [9]. These scintillator hodoscopes and wire tracking chambers provided a measurement of an event's charged-particle multiplicity and an overall view of its topology. In contrast, the spectrometer arm sampled only a small solid angle (0.68 sr), but was instrumented with an analyzing magnet, tracking chambers, and time-of-flight (TOF) counters. Detector details are discussed elsewhere [10]. For the photon data taking, the configuration of the spectrometer arm was modified by turning off the magnet, removing the TOF counters and magnet tracking chambers, and adding a NaI calorimeter. The calorimeter subtended an azimuthal angle of $1.0° \leq \phi \leq 18.1°$ and a pseudorapidity interval of $-0.16 \leq \eta \leq 0.37$. A plan view of the apparatus in this configuration is shown in Fig. 1.

The electromagnetic calorimeter, made from 36 hexagonal NaI(Tl) crystals, was placed directly behind the straw tube chambers about 2 m from the beam line. Each crystal's largest diameter was 6 in. Thirteen of the crystals were 10 radiation lengths (X_0) deep; the remaining blocks were 20 radiation lengths deep. The longer blocks were sufficiently deep to contain >98% of a 5 GeV shower. The crystals were stacked in a rectangular array with the

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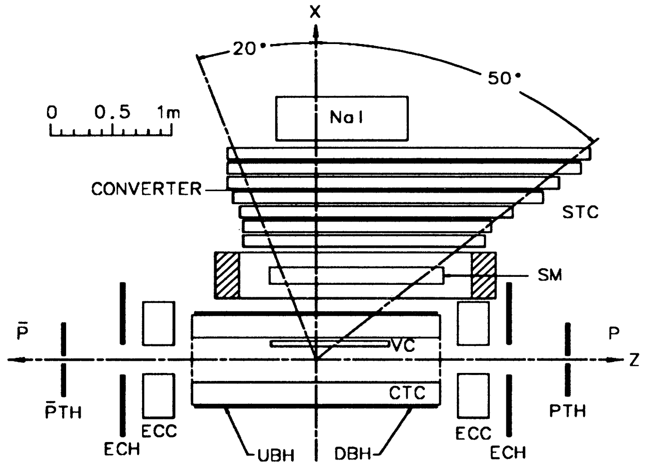

FIG. 1. A plan view of the E735 apparatus. ($\overline{\text{P}}$TH/PTH: $\bar{p}$ and p trigger hodoscopes; UBH/DBH: upstream and downstream barrel hodoscopes; ECH: end cap hodoscopes; CTC: central tracking chamber; ECC: end cap chambers; VC: vertex chamber; SM: spectrometer magnet; STC: straw tube chambers; NaI: electromagnetic calorimeter.)

shorter blocks on the sides. Overall the calorimeter was 61 cm tall and 106 cm wide. The front of the array was covered by the straw tube chambers; the remaining five sides were covered by plastic scintillating paddles.

The response along the length of the NaI crystals was measured to be uniform to 1.5%. The photomultiplier response was found to be linear over the photon energy range measured in this experiment [11]. The gains were monitored throughout the run and found to be stable within 2%. The NaI crystals were calibrated using two energy points. An Am/Be source provided 4.4 MeV photons for the first calibration point. Minimum-ionizing particles passing through the length of the crystals provided the second calibration point. These particles deposited approximately 250 MeV (125 MeV) in the longer (shorter) blocks. The measured resolution was

$$(\sigma_E/E)^2 = (2.6\%/E^{1/4})^2 + (3.6\%)^2,$$

where the photon energy E is measured in GeV. Because of the small geometric acceptance of the calorimeter, reconstruction of $\pi^0 \to \gamma\gamma$ decays was possible only for π^0's with an energy ≥ 1 GeV. Reconstruction of the π^0 mass from these data verified the calibration at high energies. The width of the reconstructed peak confirmed the resolution expected from the above formula.

Data were taken over a two month period during the 1988–89 run of the Tevatron collider. The data set contained approximately 1.7×10^6 events. Most ($\approx$80%) were taken with a trigger which enhanced the number of events with high charged-particle multiplicities by prescaling events with lower multiplicities. The other events were taken with a minimum-bias trigger. In the analysis, events taken with the high-multiplicity trigger were rescaled to recover a minimum-bias multiplicity distribution.

Once the energy deposited in each block was found, the blocks were clustered into showers, and the showers were divided into five categories. The "charged" category consisted of showers correlated with tracked charged particles. The second category consisted of showers initiated by neutral hadrons. A cut was made on the calculated lateral size of a shower. If this radius was greater than 8 cm then the shower was identified as a "neutral hadron" shower. A Monte Carlo simulation of the calorimeter showed that this cut removed a negligible fraction of the photons while removing nearly one-third of the showers caused by neutral hadrons. The third category was a sample of showers from converted photons. A thin copper plate ($0.1X_0$) in the middle of the straw tube chambers converted a small fraction of the photons into e^+e^- pairs. These pairs left a track segment behind the plate in the straw tube chambers. Any shower with a track stub pointing to it was identified as a "converted photon" shower.

The primary photon data consisted of showers not in the above categories. To ensure that the photon sample was as pure as possible, a cut was made on the number of wire hits in a road in front of a shower. Photon I showers were required to have no more than one hit behind and one hit in front of the copper plate and no hits in the last two straw tube chambers. Showers not meeting these criteria were placed in the photon II category. The shape of the photon spectrum was determined from the photons in the photon I category while the normalization was determined from the number of photons in both the photon I and II categories. Table I lists the raw number of showers in each category.

The photon I data sample consisted of photon and neutral hadron showers with a negligible contamination from charged particles because of a highly efficient (>99%), wire chamber charged-particle veto. As discussed above, the contamination from neutral hadrons was suppressed using a cut on the lateral size of the showers, with the remaining neutral hadron background subtracted using the following procedure. Fits to the measured p_t spectra of p's, $\bar{p}$'s, and $K^{\pm}$'s were used to approximate p_t spectra of n's, $\bar{n}$'s, and K^0_L's, respectively [12]. A Monte Carlo simulation showered these neutral hadrons in the NaI calorimeter, and the resulting data were put through

TABLE I. Raw number of showers by type.

Shower type	Number	Fraction (%)
Photon I	297 005	46.9
Photon II	112 958	17.8
Converted photons	19 455	3.1
Charged	185 642	29.3
Neutral hadrons	17 995	2.8
Total	633 055	100.0

the full reconstruction algorithm. Using our measured charged-particle ratios [12] and the number of "charged" showers, the neutral hadron spectra were normalized to and subtracted from the photon I spectrum. For most of the p_t range, this background comprised less than 5% of the raw spectrum. However, around 2 GeV, the fraction peaked at 25% because of $\bar{n}$ annihiliations in the crystals.

The largest single source of background consisted of photons from secondary particle interactions in the material in and around the spectrometer. The converted photon sample was used to determine this background. By extrapolating the converted photon's track segment back to the beam line, the apparent origin of each converted photon and the difference between the apparent origin and the primary interaction vertex were determined. Analyzing these differences as a function of p_t allowed us to determine the fraction of background $B(p_t) = 0.34 + 60.0\, p_t^{-1.50}$ where p_t is in MeV/c. The total percentage error on $B(p_t)$ was 6% over most of the p_t range of interest.

To recover the true photon spectrum, the background-subtracted spectrum was then deconvoluted with a detector resolution function determined from a Monte Carlo simulation of the calorimeter [11].

For a subset of the data, the integrated luminosity was calculated using the Tevatron collider's measured parameters [13]. From this and the number of events (adjusted for trigger efficiency), an effective E735 trigger cross section of $\sigma_{\rm E735} = 31.1 \pm 4.3$ mb was determined. The full data sample was normalized to $\sigma_{\rm E735}$ giving a total integrated luminosity of $1.73 \pm 0.35\,\mathrm{nb}^{-1}$ where the error is dominated by a 20% systematic uncertainty [11].

The inclusive photon differential cross section is presented in Fig. 2. This is corrected for the background and detector resolution effects described above, and the errors shown include the uncertainties in these corrections added in quadrature to the statistical errors. The 20% overall normalization error from our determination of the integrated luminosity is not included in the error bars. The measurement extends from a photon p_t of 30 MeV/c to about 5 GeV/c. At the lower end of this spectrum errors are dominated by uncertainties in the photon background from secondary particle interactions, while neutral hadron backgrounds and limited statistics dominate the errors at high p_t. The average photon p_t below 5 GeV/c is 192 ± 7 MeV/c, where we have extrapolated the photon spectrum below 30 MeV/c using a model described below.

In order to search for a possible excess of low-energy photons, the measured inclusive photon spectrum was compared to that expected from the decay of hadrons. We used fits from our measurements of the inclusive p_t spectra of $\pi^{\pm}$'s, $K^{\pm}$'s, Λ^0's, $\bar{\Lambda}^0$'s, Ξ^0's, and $\bar{\Xi}^0$'s to estimate the spectrum of photons from π^0, K, Σ, and Ξ decays [12,14]. To a first approximation, the π^0 production spectrum can be related to that measured for the $\pi^{\pm}$ by isotopic spin symmetry. Photons from the decay of the sigma hyperons were included by assuming that half of the measured lambdas come from neutral Σ decays and then using isotopic spin symmetry for the $\Sigma^{\pm}$'s [15]. An additional source of photons comes from the decay of η mesons. The production of η's was assumed to be isotropic in rapidity and distributed in p_t according to the spectrum $dN/dp_t^2 = A\exp(-p_t/b)$ with $b = 280$ MeV/c. The parameter b was estimated from an interpolation of measured p_t^2 slopes from the spectra of other hadrons. A ratio $\eta/\pi^{\pm} = 7.3\%$ was determined from an interpolation of the particle ratios from other hadrons.

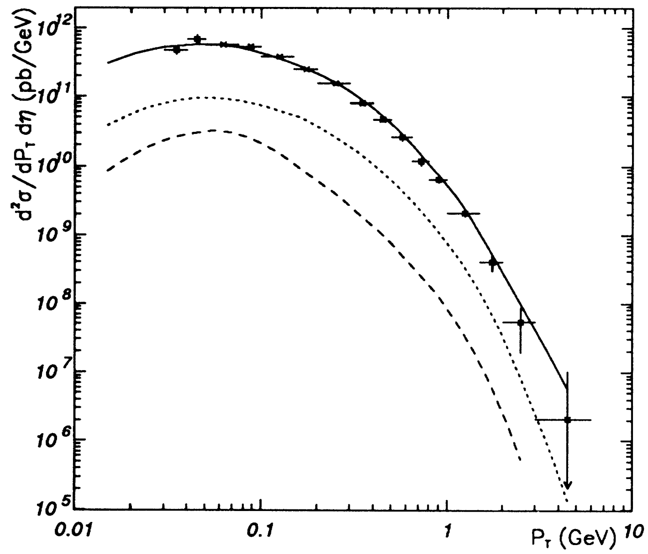

FIG. 2. The measured inclusive photon differential cross section from minimum-bias $p\bar{p}$ collisions compared to the photon spectrum expected from the electromagnetic decay of hadrons (solid curve). The contributions from η decays (dotted) and from hadron decays other than π^0's and η's (dashed) are also shown.

Figure 2 shows a comparison between the measured inclusive photon spectrum and that predicted (solid curve) from the hadron decay model described above. The model prediction was normalized to the number of photons in the data. The spectrum is dominated by photons from π^0 decays, with a 16% contribution from η decays (dotted curve) and only 4% from all other hadron decays (dashed curve). The agreement between the predicted photon spectrum and the data is reasonably good (χ^2/d.o.f. $= \tilde{\chi}^2 = 1.8$) [16]. This is shown in more detail in Fig. 3(a) where fractional differences between the measured and predicted spectra are shown. To determine the sensitivity of the predicted photon spectrum to the η cross section, the $\eta/\pi^{\pm}$ was varied. Doubling the $\eta/\pi^{\pm}$ ratio to 14.7% gives a $\tilde{\chi}^2$ of 1.6. Assuming no η production gives a $\tilde{\chi}^2$ of 2.2.

To determine an upper limit on the number of excess photons, the model prediction was normalized to

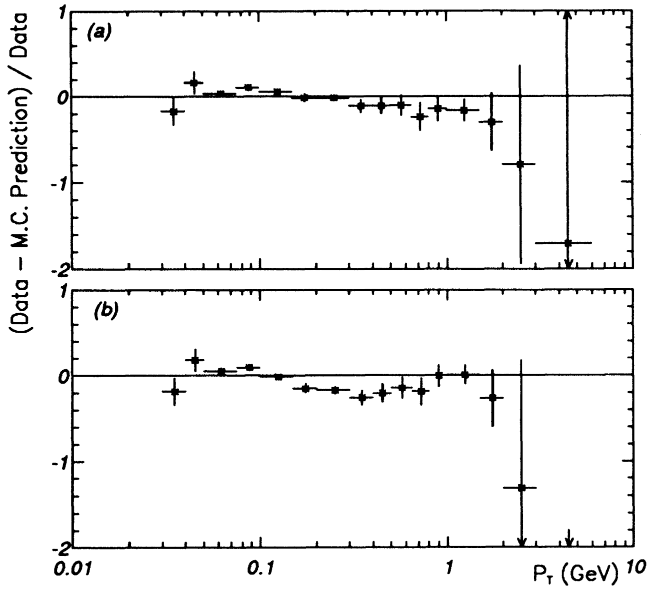

FIG. 3. Fractional difference between the measured cross section and the predictions of (a) the empirical E735 model and (b) PYTHIA.

the number of photons in the data with $p_t \geq 100$ MeV/c. The difference between the model's prediction and the number of measured photons was calculated and divided by the model's prediction. This fractional excess is $(9.2 \pm 4.0)\%$ giving a limit of 16% (90% C.L.) for photons with $30 \leq p_t \leq 100$ MeV/c. A similar calculation gives a fractional excess of $(3.0 \pm 11)\%$ and a limit of 21% (90% C.L.) for photons with $30 \leq p_t \leq 50$ MeV/c. In this p_t range, the photon contribution from hadronic inner bremsstrahlung was estimated from the measured charged-particle spectrum and found to be less than 1%.

The inclusive photon cross section was also compared to the prediction from the PYTHIA Monte Carlo program [17]. PYTHIA is a general particle production model which uses tree-level QCD and a string fragmentation scheme. PYTHIA did not fit the data well ($\tilde{\chi}^2 = 4.6$). The fractional differences between PYTHIA's prediction and the measured cross section are shown in Fig. 3(b). The disagreement is caused by PYTHIA's poor reproduction of the low-p_t $\pi^\pm$ spectrum as measured in the E735 experiment.

In conclusion, we find that the measured differential inclusive photon cross section from $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV and the spectrum expected from the electromagnetic decays of hadrons agree for photons with $p_t < 5$ GeV/c. In particular, there is no evidence for an anomalous source of low-energy photons down to a p_t of 30 MeV/c.

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[1] G. Staadt *et al.*, Phys. Rev. D **33**, 66 (1986); M. Neubert *et al.*, Z. Phys. C **42**, 231 (1989).
[2] F.E. Low, Phys. Rev. **110**, 974 (1958); T.H. Burnett and M. Kroll, Phys. Rev. Lett. **20**, 86 (1968).
[3] V.V. Goloviznin *et al.*, Z. Phys. C **38**, 255 (1988).
[4] P.V. Chliapnikov *et al.*, Phys. Lett. **141B**, 276 (1984).
[5] F. Botterweck *et al.*, Z. Phys. C **51**, 541 (1991).
[6] L. Van Hove, Ann. Phys. (N.Y.) **192**, 66 (1989); P. Lichard and L. Van Hove, Phys. Lett. B **245**, 605 (1990).
[7] A.T. Goshaw *et al.*, Phys. Rev. Lett. **43**, 1065 (1979); T. Åkesson *et al.*, Phys. Rev. D **36**, 2615 (1987); **38**, 2687 (1988); Z. Phys. C **46**, 369 (1990); R. Albrecht *et al.*, *ibid.* **51**, 1 (1991).
[8] J. Antos *et al.*, CERN Report No. CERN-PPE/93-36, 1993 (to be published).
[9] The positive η direction is along the $+z$ axis.
[10] S. Banerjee *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **269**, 121 (1988); C. Allen *et al.*, *ibid.* **294**, 108 (1990); E.W. Anderson *et al.*, *ibid.* **295**, 86 (1990); S.H. Oh *et al.*, *ibid.* **303**, 277 (1991); T. Alexopoulos *et al.*, *ibid.* **311**, 156 (1992).
[11] Charles A. Loomis, Jr., Ph.D. thesis, Duke University, 1992.
[12] T. Alexopoulos *et al.*, Phys. Rev. D **48**, 984 (1993).
[13] N. Gelfand, Fermilab Report No. FN-538, 1990 (unpublished).
[14] T. Alexopoulos *et al.*, Phys. Rev. D **46**, 2773 (1992).
[15] Weak decays resulting in π^0's are properly excluded when already included from the $\pi^\pm \to \pi^0$ simulation.
[16] The accuracy of the predicted photon spectrum is limited by our extrapolation to higher p_t of the fit to the measured $\pi^\pm$ spectrum.
[17] Hans-Uno Bengtsson and Törbjorn Sjöstrand, Comput. Phys. Commun. **46**, 43 (1987).