Observation of Direct Photons in Central 158*A* GeV ^{208}Pb + ^{208}Pb Collisions

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A measurement of direct photon production in ^{208}Pb + ^{208}Pb collisions at 158*A* GeV has been carried out in the CERN WA98 experiment. The invariant yield of direct photons in central collisions is extracted as a function of transverse momentum in the interval $0.5 < p_T < 4$ GeV/c. A significant direct photon signal, compared to statistical and systematical errors, is seen at $p_T > 1.5$ GeV/c. The result constitutes the first observation of direct photons in ultrarelativistic heavy-ion collisions. It could be significant for diagnosis of quark-gluon-plasma formation.

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The observation of a new phase of strongly interacting matter, the quark-gluon plasma (QGP), is one of the most important goals of current nuclear physics research. An extensive experimental program has been undertaken at the CERN SPS accelerator with Pb-ion beams of 158*A* GeV to search for and investigate the QGP. Several observations, such as suppression of the J/ψ resonance [1] and the enhancement of strangeness [2], hint at an interesting new behavior of the matter produced in these collisions. While such observations imply a hot and dense initial phase with strong rescattering, consistent with the assumption that a quark-gluon plasma was formed, a direct signature of the plasma and its properties is missing. It is therefore of great interest to search for photons emitted directly from the early hot phase of the relativistic heavy-ion collisions.

Following early estimates of photon emission rates [3–6], Kapusta *et al.* [7] made detailed comparisons of the emissivity of the QGP and a hadron gas as two contrasting scenarios. It was demonstrated that the thermal emission rates of a hadron gas and a QGP were very similar and dependent essentially only on the temperature T. This led the authors to conclude that direct photons are a good thermometer for strongly interacting matter, but would not in themselves allow one to distinguish between the two scenarios.

Recently, it was shown by Aurenche *et al.* [8] that photon production rates in the QGP, when calculated up to two-loop diagrams, are considerably greater than the earlier lowest order estimates. A new higher order process of $q\overline{q}$ annihilation with rescattering was found to dominate the photon emission rate from quark matter at high photon energies. Following this result, Srivastava [9] reinvestigated the predicted photon production in heavy-ion collisions and showed that at sufficiently high initial temperatures the photon yield from quark matter may significantly exceed the contribution from the hadronic matter to provide a direct probe of the quark matter phase.

A large number of measurements of prompt photon production at high transverse momentum ($p_T > 3$ GeV$/c$) exist for proton-proton, proton-antiproton, and proton-nucleus collisions (see e.g., Ref. [10]). To a great extent, especially at higher $\sqrt{s}$, these data can be successfully described by perturbative quantum chromodynamics calculations and provide an important foundation from which to study photon production in nucleus-nucleus collisions. First attempts to observe direct photon production in ultrarelativistic heavy-ion collisions with oxygen and sulphur beams found no significant excess [11–14]. The WA80 Collaboration [14] provided the most interesting result with a p_T dependent upper limit on the direct photon production in S + Au collisions at 200*A* GeV. This result was subsequently used by several authors to rule out a simple version of the hadron gas scenario [15–18] and has been interpreted to set an upper limit on the initial temperature of $T_i = 250$ MeV [19].

In this paper we report on the first observation of direct photon production in ultrarelativistic heavy-ion collisions. The results are from the CERN experiment WA98 [20] which consists of large acceptance photon and hadron spectrometers. In addition, several other large acceptance devices allow one to measure various global variables on an event-by-event basis for event characterization. Photons are measured with the WA98 lead-glass photon detector, LEDA, which consisted of 10 080 individual modules with photomultiplier readout. The detector was located at a distance of 21.5 m from the target and covered the pseudorapidity interval $2.35 < \eta < 2.95$ ($y_{cm} = 2.9$). The particle identification was supplemented by a charged particle veto detector in front of LEDA.

The results presented here were obtained from an analysis of the data taken with Pb beams in 1995 and 1996. The 20% most peripheral and the 10% most central reactions have been selected from the minimum-bias cross section ($\sigma_{\text{min-bias}} \approx 6300$ mb) using the measured transverse energy E_T. In total, $\approx 6.7 \times 10^6$ central and $\approx 4.3 \times 10^6$ peripheral reactions have been analyzed.

The extraction of direct photons in the high multiplicity environment of heavy-ion collisions must be performed on a statistical basis by comparison of the measured inclusive photon spectra to the background expected from hadronic decays. Individual photons cannot be tagged as isolated direct photons in these reactions due to the high multiplicities. To obtain the direct photon spectrum the following steps are performed (for a detailed description of the detectors and the analysis procedure, see Ref. [21]): The raw photon spectra are accumulated after application of the photon identification criteria (such as transverse shower size) to the showers observed in the LEDA. The raw photon spectra are then corrected for contamination by charged and neutral hadrons, for conversions, for the identification efficiency, and for acceptance. The efficiency includes all effects of the detector response such as distortions by shower overlap, dead and bad modules, and energy resolution. Neutral pions are reconstructed via their $\gamma\gamma$ decay branch. Invariant mass spectra are accumulated for all photon pairs for each pair p_T bin. The photon-pair combinatorial background is estimated by event mixing and then subtracted from the real-pair spectra. The yield in the π^0 mass peak is extracted to obtain the raw neutral pion p_T spectra. These are then corrected for conversions, for the π^0 identification efficiency, and for geometrical acceptance. In addition, η mesons are extracted in a limited transverse momentum range with an analogous procedure.

The final measured inclusive photon spectra are then compared to the calculated background photon spectra to check for a possible photon excess beyond that from long-lived radiative decays. The background calculation is based on the measured π^0 and η spectra. The measured η/π^0 ratio is found to be consistent with m_T scaling [21,22] which is assumed for the spectral shapes of the η and for other unmeasured hadrons having radiative decays.

The unmeasured hadron yields relative to π^0's are taken from the literature [21]. It should be noted that the measured contribution (from π^0 and η) amounts to $\approx$97% of the expected total photon background.

Figure 1 shows the fully corrected inclusive photon spectra for peripheral and central collisions. The spectra cover the p_T range of 0.3–4.0 GeV/c (slightly less for peripheral collisions) and extend over 6 orders of magnitude. Figure 1 also shows the distributions of neutral pions which extend over a similar momentum range with slightly larger statistical errors. The calculated decay photon background is shown by the solid curves.

The ratio of measured photons to calculated background photons is displayed in Fig. 2 as a function of transverse momentum. The upper plot shows the ratio for peripheral collisions which is seen to be compatible with 1, i.e., no indication of a direct photon excess is observed. The lower plot shows the same ratio for central collisions. It rises from a value of $\approx$1 at low p_T to exhibit an excess of about 20% at high p_T.

A careful study of possible systematical errors is crucial for the direct photon analysis. The various sources of systematical errors have been investigated and are summarized in Table I. The largest contributions are from the γ and π^0 identification efficiencies and the uncertainties related to the η measurement. It should be emphasized that the inclusive photon, π^0, and η yields have been extracted with the same detector for exactly the same data sample. This decreases the sensitivity to many detector related errors and eliminates all errors associated with trigger bias or absolute yield normalization. The estimate of the systematical errors has been checked by performing the entire analysis with various photon selection criteria which change the efficiency and background corrections by factors of 2–3. The final results were verified to be consistent within the systematical errors for the different analysis cuts. Full details on the systematical error estimates are given in [21]. The total p_T dependent systematical errors are shown by the shaded regions in Fig. 2. A significant photon excess is clearly observed in central collisions for $p_T > 1.5$ GeV/c.

The final invariant direct photon yield per central collision is presented in Fig. 3. The statistical and asymmetric systematical errors of Fig. 2 are added in quadrature to obtain the total upper and lower errors shown in Fig. 3. An additional p_T dependent error is included to account for that portion of the uncertainty in the energy scale which cancels in the ratios. In the case that the lower error is less than zero, a downward arrow is shown with the tail of the arrow indicating the 90% confidence level (C.L.) upper limit ($\gamma_{\text{excess}} + 1.28\sigma_{\text{upper}}$).

No published prompt photon results exist for proton-induced reactions at the $\sqrt{s}$ of the present measurement. Instead, prompt photon yields for proton-induced reactions on fixed targets at 200 GeV are shown in Fig. 3 for comparison. Results are shown from FNAL experiment E704 [23] for proton-proton reactions, and from FNAL experiment E629 [24] and CERN SPS experiment NA3 [25] for proton-carbon reactions. These results have been divided by the total pp inelastic cross section ($\sigma_{\text{int}} = 30$ mb)

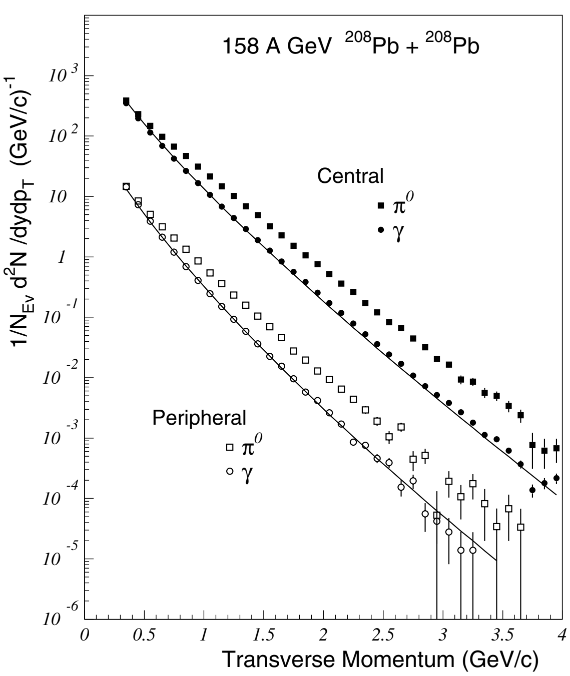

FIG. 1. The inclusive photon (circles) and π^0 (squares) transverse momentum distributions. Only statistical errors are shown.

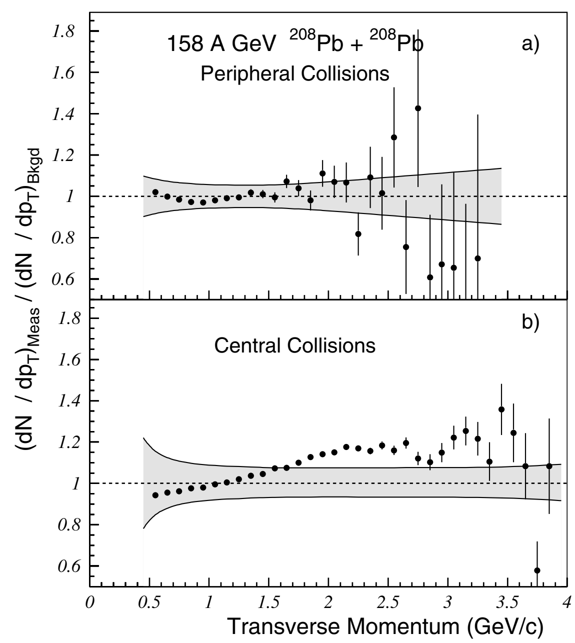

FIG. 2. The ratio of measured-to-calculated background photons as a function of transverse momentum for peripheral [part (a)] and central [part (b)] 158A GeV ^{208}Pb + ^{208}Pb collisions. The errors on the data points indicate the statistical errors only. The p_T dependent systematical errors are indicated by the shaded bands.

TABLE I. Various sources of systematical error in the WA98 158A GeV ^{208}Pb + ^{208}Pb direct photon analysis specified as a percentage of $(\gamma/\pi^0)_{\rm meas}$ (items a), $(\gamma/\pi^0)_{\rm bkgd}$ (items b), or $(\pi^0)_{\rm meas}/(\pi^0)_{\rm bkgd}$ (item c). The systematical errors are quoted at two p_T values to give an indication of the dependence on transverse momentum. See Ref. [21] for full details.

Source of Error	Peripheral Collisions (20% $\sigma_{\rm mb}$)		Central Collisions (10% $\sigma_{\rm mb}$)	
	$p_T \approx 1.0$ GeV/c	$p_T \approx 2.5$ GeV/c	$p_T \approx 1.0$ GeV/c	$p_T \approx 2.5$ GeV/c
(a) γ yield measurement	2.7	3.2	2.6	3.1
(a) π^0 yield measurement	3.1	3.0	6.5	4.2
(a) Nontarget background	1.5	<0.1	<0.1	<0.1
(a) Energy scale calibration	0.9	1.7	0.8	1.7
(b) Detector acceptance	0.5	0.5	0.5	0.5
(b) η/π ratio, m_T scaling	2.9	3.2	+3.4 (−4.8)	+3.7 (−5.2)
(b) Other radiative decays	1.0	1.0	1.0	1.0
(c) π^0 fit	1.6	6.8	2.9	0.4
Total: (quadratic sum)	5.7	8.9	+8.3 (−9.1)	+6.7 (−7.6)

and by the mass number of the target to obtain the invariant direct photon yield per nucleon-nucleon collision. They have then been multiplied by the calculated average number of nucleon-nucleon collisions (660) for the central Pb + Pb event selection for comparison with the present measurements. This scaling is estimated to have an uncertainty of less than 10%. The proton-induced results have also been scaled from $\sqrt{s} = 19.4$ GeV to the lower $\sqrt{s} = 17.3$ GeV of the present measurement under the assumption that $Ed^3\sigma_\gamma/dp^3 = f(x_T)/s^2$, where $x_T = 2p_T/\sqrt{s}$ [26]. The $\sqrt{s}$ scaling effectively reduces the 19.4 GeV proton-induced results by about a factor of 2. This comparison indicates that the observed direct photon production in central ^{208}Pb + ^{208}Pb collisions has a shape similar to that expected for proton-induced reactions at the same $\sqrt{s}$ but a yield which is enhanced.

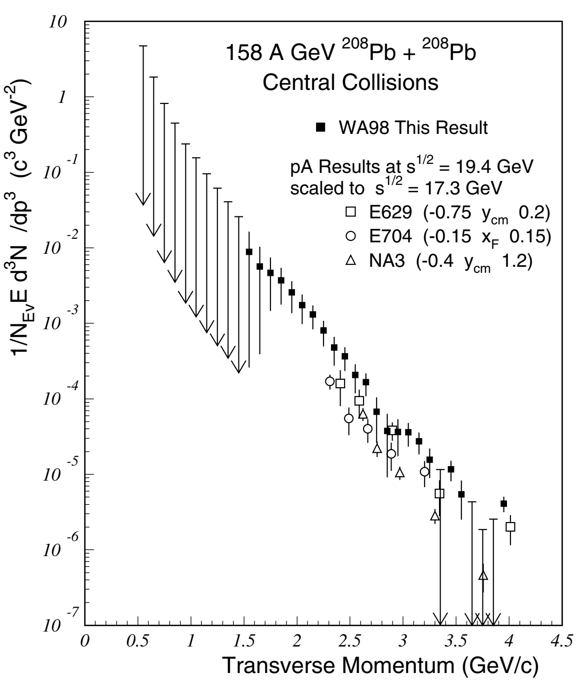

FIG. 3. The invariant direct photon multiplicity for central 158A GeV ^{208}Pb + ^{208}Pb collisions. The error bars indicate the combined statistical and systematical errors. Data points with downward arrows indicate unbounded 90% C.L. upper limits. Results of several direct photon measurements for proton-induced reactions have been scaled to central ^{208}Pb + ^{208}Pb collisions for comparison.

In summary, the first observation of direct photons in ultrarelativistic heavy-ion collisions has been presented. While peripheral Pb + Pb collisions exhibit no significant photon excess, the 10% most central reactions show a clear excess of direct photons in the range of p_T greater than about 1.5 GeV/c. The invariant direct photon multiplicity as a function of transverse momentum was presented for central ^{208}Pb + ^{208}Pb collisions and compared to proton-induced results at similar incident energy. The comparison suggests excess direct photon production in central ^{208}Pb + ^{208}Pb collisions beyond that expected from proton-induced reactions. The result suggests modification of the prompt photon production in nucleus-nucleus collisions, or additional contributions from preequilibrium or thermal photon emission. The result should provide a stringent test for different reaction scenarios, including those with quark-gluon-plasma formation, and may provide information on the initial temperature attained in these collisions.

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