Direct Photon Production in 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 results constitute the first observation of direct photons in ultrarelativistic heavy-ion collisions which could be significant for diagnosis of quark gluon plasma formation.

1. Introduction

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. To study QGP formation photons (both real and virtual) were one of the earliest proposed signatures [3,4]. They are likely to escape from the system directly after production without further interaction, unlike hadrons. Thus, photons carry information on their emitting sources from throughout the entire collision history, including the initial hot and dense phase. Recently, it was shown by Aurenche et al. [5] that photon production rates in the QGP when calculated up to two loop diagrams, are considerably greater than the earlier lowest order estimates[6]. Following this result, Srivastava [7] has shown 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. [8]). First attempts to observe direct photon production in ultrarelativistic heavy-ion collisions with oxygen and sulphur beams found no significant excess [9,12]. The WA80 collaboration [12] provided the most interesting result with a $p_T$ dependent upper limit on the direct photon production in S+Au collisions at 200AGeV. In this paper we report on the first observation of direct photon production in ultrarelativistic heavy-ion collisions.

We will also present results of a study of the scaling behavior of charged particle multiplicities as a function of the centrality of the collision, which may carry important information on the reaction dynamics.
Figure 1. The inclusive photon (circles) and $\pi^0$ (squares) transverse momentum distributions for peripheral (open points) and central (solid points) 158 A GeV $^{208}$Pb + $^{208}$Pb collisions. The data have been corrected for efficiency and acceptance. Only statistical errors are shown.

2. Direct Photon Production

2.1. Data Analysis

The results are from the CERN experiment WA98 [13] which consists of large acceptance photon and hadron spectrometers. 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, $\approx 6.7 \cdot 10^6$ central and $\approx 4.3 \cdot 10^6$ 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. Neutral pions and $\eta$...
mesons are reconstructed via their $\gamma\gamma$ decay branch. For a detailed description of the detectors and the analysis procedure see [14].

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 $\pi^0$ spectra and the measured $\eta/\pi^0$-ratio. The spectral shapes of other hadrons having radiative decays are calculated assuming $m_T$-scaling [13] with yields relative to $\pi^0$'s taken from the literature. It should be noted that the measured contribution (from $\pi^0$ and $\eta$) amounts to $\approx 97\%$ of the total photon background.

2.2. Results

Fig. 1 shows the fully corrected inclusive photon spectra for peripheral and central collisions. The spectra cover the $p_T$ range of $0.3 - 4.0\,\text{GeV/c}$ (slightly less for peripheral collisions) and extend over six orders of magnitude. Fig. 1 also shows the distributions of neutral pions which extend over a similar momentum range with slightly larger statistical
Figure 3. The invariant direct photon multiplicity for central 158 A GeV $^{208}$Pb+$^{208}$Pb collisions. The error bars indicate the combined statistical and systematical errors. Data points with downward arrows indicate unbounded 90% CL upper limits. Results of several direct photon measurements for proton-induced reactions have been scaled to central $^{208}$Pb+$^{208}$Pb collisions for comparison.

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 one, 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 largest contributions are from the $\gamma$ and $\pi^0$ identification efficiencies and the uncertainties related to the $\eta$ measurement. It should be emphasized that the inclusive photon and neutral meson (the basis for the background calculation) yields have been extracted from 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. Full details on the systematical error estimates...
Figure 4. Ratio of the direct photon multiplicity to fits to the neutral pion multiplicity obtained within the same experiments. Shown are the present data for central 158 A GeV $^{208}$Pb+$^{208}$Pb collisions (filled circles). The error bars indicate the combined statistical and systematical errors. Results of measurements for proton-induced reactions are shown as open symbols. The dotted lines indicate linear fits to the p+p and p+C data, resp. are given in [14]. 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 upper limit ($\gamma_{Excess} + 1.28 \sigma_{Upper}$).

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 [10] [18]. These results have been scaled for comparison with the present measurements according to the calculated average number of nucleon-nucleon collisions (660) for the central Pb+Pb event selection.
and according to the beam energy under the assumption that \( E d^3\sigma/dp^3 = f(x_T)/s^2 \), where \( x_T = 2p_T/\sqrt{s} \) \([13]\). This comparison indicates that the observed direct photon production in central \(^{208}\text{Pb} + ^{208}\text{Pb}\) collisions has a shape similar to that expected for proton-induced reactions at the same \( \sqrt{s} \) but a yield which is enhanced.

Because of possible uncertainties in the scaling of the proton induced results related to the absolute normalization of the earlier data sets and to possible, but as yet undetermined changes in the intrinsic \( k_T \) at the lower \( \sqrt{s} \), we have performed a comparison of the ratio of direct photons to neutral pions \( \gamma_{\text{direct}}/\pi^0 \) for the different data sets which is displayed in Fig. 4. A comparison of this ratio is not so sensitive to the above uncertainties, but has to assume a similar scaling behavior of direct photons and neutral pions, which leads to a different uncertainty in the interpretation. Fig. 4 indicates a good agreement of the \( \gamma_{\text{direct}}/\pi^0 \) ratio at high \( p_T \), but an excess in this ratio for \( 1.5 \text{ GeV}/c \leq p_T \leq 2.5 \text{ GeV}/c \) not expected from an extrapolation of the proton induced results.

### 3. Scaling of Particle Production

![Figure 5](image_url)

Figure 5. a) Charged particle yields at midrapidity in 158-\( A \) GeV Pb+Pb reactions normalized to the number of participants as a function of the number of participants. b) Pseudorapidity density of \( N_{\text{ch}} \) at midrapidity as a function of the number of participants for p+p \([24]\) and Pb+Pb collisions. The fit function included is obtained by fitting all Pb+Pb data points included in (a).

The charged particle multiplicity is measured with a circular Silicon Pad Multiplicity Detector (SPMD) located 32.8 cm downstream of the target \([20]\). It provides full azimuthal coverage of the pseudorapidity region \( 2.35 < \eta < 3.75 \). The charged particle scaling has been investigated with the centrality of the Pb+Pb collision determined from the transverse energy, \( E_T \), measured with the MIRAC calorimeter. The number of par-
participants $N_{\text{part}}$ for a given centrality class has been determined from a simulation based on the event generator VENUS 4.12 \cite{21}. Details on the analysis and the estimates of the number of participants can be found in \cite{22}.

Fig. 5a) shows the charged particle yields at midrapidity normalized to the number of participants as a function of the number of participants. It can be clearly seen that the multiplicity increases stronger than linearly with the number of participants which contradicts the expectations from the Wounded Nucleon Model \cite{23}. The scaling behavior was parameterized as

$$\left. \frac{dN_{\text{ch}}}{d\eta} \right|_{\text{max}} \sim N_{\text{part}}^\alpha.$$  \hspace{1cm} (1)

This functional dependence gives a reasonable description of the data for the whole centrality range. The $N_{\text{ch}}$ scaling with the number of participants can be described by a scaling exponent $\alpha = 1.08 \pm 0.03$. In Fig. 5b) the scaling behavior is shown in more detail for small numbers of participants. The corresponding value for p+p reactions is shown, which nicely agrees with an extrapolation of the parameterization.

4. 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 $^{208}\text{Pb}+^{208}\text{Pb}$ collisions and compared to proton-induced results at similar incident energy. The comparison indicates excess direct photon production in central $^{208}\text{Pb}+^{208}\text{Pb}$ 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 pre-equilibrium 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.

In addition, we have demonstrated that the charged particle multiplicity increases stronger than linearly with the number of participants.

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