Limits on the Production of Direct Photons in 200A GeV ^{32}S + Au Collisions

R. Albrecht,[1] V. Antonenko,[2] T. C. Awes,[3] C. Barlag,[4] F. Berger,[4] M. Bloomer,[5] C. Blume,[4] D. Bock,[4] R. Bock,[1] E.-M. Bohne,[4] D. Bucher,[4] G. Claesson,[6] A. Claussen,[4] G. Clewing,[4] R. Debbe,[7] L. Dragon,[4] Yu. Dubovik,[2] A. Eklund,[6] S. Fokin,[2] A. Franz,[8] S. Garpman,[6] R. Glasow,[4] H. Å. Gustafsson,[6] H. H. Gutbrod,[1] O. Hansen,[7] G. Hölker,[4] J. Idh,[6] M. Ippolitov,[2] P. Jacobs,[5] K. H. Kampert,[4] K. Karadjev,[2] B. W. Kolb,[1] A. Lebedev,[2] H. Löhner,[9] I. Lund,[1] V. Manko,[2] B. Moskowitz,[7] S. Nikolaev,[2] J. Nystrand,[6] F. E. Obenshain,[3] A. Oskarsson,[6] I. Otterlund,[6] T. Peitzmann,[4] F. Plasil,[3] A. M. Poskanzer,[5] M. Purschke,[4] H.-G. Ritter,[5] B. Roters,[4] S. Saini,[3] R. Santo,[4] H. Schlagheck,[4] H. R. Schmidt,[1] K. Söderström,[6] S. P. Sørensen,[3,8] P. W. Stankus,[3] K. Steffens,[4] P. Steinhaeuser,[4] E. Stenlund,[6] D. Stüken,[4] A. Vinogradov,[2] H. Wegner,[7,*] and G. R. Young[3]

(WA80 Collaboration)

[1]*Gesellschaft für Schwerionenforschung, D-64291 Darmstadt, Germany*
[2]*Kurchatov Institute of Atomic Energy, Moscow 123182, Russia*
[3]*Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831*
[4]*University of Münster, D-48149 Münster, Germany*
[5]*Lawrence Berkeley Laboratory, Berkeley, California 94720*
[6]*University of Lund, S-22362 Lund, Sweden*
[7]*Brookhaven National Laboratory, Upton, New York 11973*
[8]*University of Tennessee, Knoxville, Tennessee 37996*
[9]*Kernfysisch Versneller Instituut, University of Groningen, NL-9747 AA Groningen, The Netherlands*

(Received 16 November 1995)

A search for the production of direct photons in S + Au collisions at 200A GeV has been carried out in the CERN-WA80 experiment. For central collisions the measured photon excess at each p_T, averaged over the range $0.5 \le p_T \le 2.5$ GeV$/c$, corresponded to 5.0% of the total inclusive photon yield with a statistical error of $\sigma_{\text{stat}} = 0.8\%$ and a systematic error of $\sigma_{\text{syst}} = 5.8\%$. Upper limits on the invariant yield for direct photon production at the 90% C.L. are presented. Possible implications for the dynamics of high-energy heavy-ion collisions are discussed. [S0031-9007(96)00150-0]

PACS numbers: 25.75.Dw

Directly radiated thermal photons have long been considered an interesting penetrating probe with which to study the early phase of the hot and dense matter produced in ultrarelativistic nucleus-nucleus collisions. Single "direct" photons are expected at high transverse momentum, p_T, from well-known hard QCD processes, but also possibly in the p_T region below several GeV$/c$ due to thermal radiation from the hot dense matter [1]. Since the mean free path of the produced photons is considerably larger than the size of the nuclear volume, photons produced throughout all stages of the collision will be observable in the final state. Thus, it is believed that the emitted photons should provide information about the initial conditions of the hot dense system and thereby provide evidence for the possible formation of a quark gluon plasma (QGP).

The search for direct photon production in ultrarelativistic nucleus-nucleus collisions has been a major emphasis of the WA80 experiment at CERN. The first results from WA80 found no excess photon yield beyond that attributable to resonance decays in central collisions of ^{16}O + Au at 200A GeV, setting an upper limit of $\gamma^{\text{direct}}/\pi^0 < 15\%$ [2]. The preliminary results of the 1990 WA80 ^{32}S + Au photon analysis showed no significant excess in peripheral collisions, while an excess at about the $\sim 2\sigma$ level was seen in central collisions [3]. Although preliminary, these results have generated a great deal of theoretical interest [4–8]. In this Letter we report the final results of the WA80 ^{32}S + Au direct photon analysis, we compare the final results to theoretical calculations, and discuss the implications towards the possible formation of a QGP.

The WA80 experimental setup for the 1990 run period with 200A GeV ^{32}S beams was upgraded from that used for the previous run periods with ^{16}O and ^{32}S beams [2,3,9]. The direct photon sensitivity for this data set, relative to the ^{16}O data [2], was improved by several factors [3] including an increased data sample, an increased detector coverage, a coverage closer to mid-rapidity, and improved analysis techniques. The WA80 photon spectrometer consisted of a finely segmented electromagnetic calorimeter composed of 3798 lead-glass modules with photomultiplier tube readout. The lead glass was arranged into three independently calibrated arrays, of roughly equal size. Two of the arrays consisted of TF1 lead-glass of 4 cm × 4 cm × 4 cm ($15X_0$) [10] deployed as towers to the left and right of the beam axis. The third array, located below the beam axis, was the SAPHIR lead-glass detector [11] used in the WA80 ^{16}O run period [2] which consisted of SF5 lead-glass modules of 3.5 cm × 3.5 cm × 46 cm ($18X_0$). The entire photon spectrometer provided coverage of from $\frac{1}{10}$ to $\frac{1}{2}$ of full ϕ over the rapidity range of $2.1 \le y \le 2.9$.

Immediately in front of the photon spectrometer was a double-layer charged-particle veto (CPV) counter which covered the lead-glass region of acceptance. Each layer of the CPV consisted of streamer tubes with charge-sensitive pad readout, with pads of dimension similar to the lead-glass modules [12].

For the direct photon analysis the total event sample of 6.27×10^6 events was divided into various centrality classes based on the measured transverse energy. The total transverse energy was measured in the WA80 mid-rapidity calorimeter [13] which had full ϕ coverage over the pseudorapidity range $2.9 \leq \eta \leq 5.5$ and partial coverage extending to $2.4 \leq \eta$. In this Letter, results are presented for the most peripheral events corresponding to 31% σ_{mb} and the most central events corresponding to 7.4% σ_{mb}, with $\sigma_{\mathrm{mb}} = 3600$ mb [14]. This central event class corresponds to the complete geometrical overlap of the S nucleus with the Au target, with an average of 107 participating nucleons (to be compared to an average of 5.6 participating nucleons for the peripheral event class), in contrast to the less restrictive centrality condition of 25% σ_{mb} used in the preliminary analysis [3,14,15].

In the WA80 experiment, the π^0 and η yields have been measured simultaneously with the inclusive photon yield, γ^{obs}, via their two-photon decay branches, in the same p_T and rapidity region for each event class used in the excess photon search [9]. This is essential in order to minimize systematic error due to the known centrality dependence of the meson p_T spectra. In this analysis the direct photon excess is determined on a statistical basis: once the spectrum of photons expected from background sources, γ^{bkgd}, has been calculated based on the measured π^0 and η yields (which nominally account for about 98% of γ^{bkgd}) with estimates of the small photon contributions from other radiative decays, one may in principle extract the photon excess as $\gamma^{\mathrm{excess}} \equiv \gamma^{\mathrm{obs}} - \gamma^{\mathrm{bkgd}}$. However, since the large majority of photons observed at a given p_T originate from the decay of π^0's at nearly the same p_T, it is in practice more convenient to work with the ratios $(\gamma/\pi^0)^{\mathrm{obs}}$ and $(\gamma/\pi^0)^{\mathrm{bkgd}}$, which are less sensitive to systematic error [2,3]. Furthermore, it is useful to study the ratio $(\gamma/\pi^0)^{\mathrm{obs}}/(\gamma/\pi^0)^{\mathrm{bkgd}}$ which indicates the fraction of photons observed relative to the expected decay background and should have a value of 1 if there are no excess photons.

Since the low p_T thermal photon excess is expected to be small in comparison to the known background sources, with likely signal/background ratios of 10% or less [1], it is imperative to minimize and accurately determine possible sources of systematic error. As indicated below, it is possible to use the WA80 data sample itself to estimate and limit most sources of systematic error. For example, the energy dependence of the measured π^0 mass peak has been used to set limits on the nonlinearity of the energy scale. The various sources of systematic error are listed in Table I together with estimated upper limits on their values for the central and peripheral data sets presented in this Letter. Complete details of the systematic error estimation will be presented in a forthcoming publication.

Individual showers were identified as a cluster of adjacent lead-glass modules with energy deposit. Overlapping showers were identified and separated using an algorithm based on finding local maxima and apportioning the energy deposited in each module in a self-consistent manner [10], though it is inevitable that some showers will have their energy modified, or be lost completely, due to the effects of overlap. These effects can, however, be understood *in situ* by using the data themselves. A large number of showers in the calorimeter (or pairs of showers) resulting from single particles produced at the target—including γ, π^0, η, $\pi^{\pm}$, $K^{\pm}$, p, n, $\overline{p}$, or $\overline{n}$—were simulated using GEANT V3.15 (the GEANT simulation parameters were adjusted so that the simulated EM showers matched test beam results). The energy deposited in each module from

TABLE I. Various sources of systematic error in the WA80 200*A* GeV ^{32}S + Au direct photon analysis specified as a percentage of $(\gamma/\pi^0)^{\mathrm{obs}}/(\gamma/\pi^0)^{\mathrm{bkgd}}$. The dependence of the errors on p_T is indicated.

	Peripheral collisions (31% σ_{mb})		Central collisions (7.4% σ_{mb})	
Source of error	$p_T < 1.5$ GeV/c	$p_T > 1.5$ GeV/c	$p_T < 1.5$ GeV/c	$p_T > 1.5$ GeV/c
γ reconstruction efficiency	1.0	1.0	2.0	2.0
π^0 yield extraction and efficiency	2.0	3.0	4.0	5.0
Detector acceptance[a]	0.5	0.5	0.5	0.5
Energy nonlinearity[a]	2.0	1.0	2.0	1.0
Binning effects[a]	1.0–0.0	0.0	1.0–0.0	0.0
Charged vs neutral shower separation[a]	1.0	1.0	1.0	1.0
γ conversion correction[a]	1.0	1.0	1.0	1.0
Neutrons	1.5	0.5	1.5	0.5
Other neutrals, e.g., $\overline{n}, K_L^0$	1.0	0.5	1.0	0.5
η/π ratio, m_t scaling	1.5	1.5	1.5	1.5
Other radiative decays	0.5	0.5	0.5	0.5
Total (quadratic sum)	4.2	4.0	5.7	5.9

[a]Centrality independent.

these simulated single-particle events was added to the energies in a real data event, and then both the original and the superimposed events were put through the identical analysis chain to reconstruct hits in the detector. Comparison of the reconstructed showers with the input GEANT particles provided the information necessary for the efficiency determination. Single, separated showers can be labeled as photons or nonphotons using different sets of criteria of varying restrictiveness. The different photon identification criteria applied were to use: (A) all showers, (B) only showers with small lateral profile, (C) only showers without an overlapping hit in either CPV layer, and (D) only showers without an overlapping hit in both CPV layers. The different criteria give rise to different photon and π^0 identification efficiencies and different background contamination corrections. In a consistent analysis, all photon identification methods should give the same final result. The variation of the final result with the photon identification method, for both single photon and π^0 measurements, has been used to check for systematic errors in the yield determination.

To determine the efficiency and hadron-contamination-corrected inclusive photon yield, two different approaches were used, one using the CPV and the other without. Various cross checks were also explored, leading to a final estimate for the systematic uncertainty of the inclusive photon yield measurement of $\leq 2\%$ (see Table I).

The major source of systematic error in the search for excess photons is the uncertainty in the π^0 yield extraction (see Table I). The yield extraction is complicated by the large photon multiplicity in nucleus-nucleus collisions which leads to modifications of the π^0 mass peak due to shower overlap. This is simultaneously accompanied by a decreasing π^0 peak-to-background ratio resulting from the increasing number of two-photon combinatorial background pairs. The centrality dependent combinatorial background in the two-photon mass distribution has been determined by an event-mixing method in which photon pairs are combined from artificial events which have been produced by taking photons from different unrelated events of the same event class. This event-mixed mass distribution closely resembles the shape of the combinatorial background distribution in both $m_{\gamma\gamma}$ and p_T. Still, in order to accurately match the combinatorial background distributions, it was found necessary to apply a small correction to the event-mixed distributions by multiplying by a weakly linear function in $m_{\gamma\gamma}$ and p_T. Typically this correction was less than 0.5% over the π^0 mass fit region.

Figure 1 shows the ratio $(\gamma/\pi^0)^{\rm obs}/(\gamma/\pi^0)^{\rm bkgd}$ as a function of p_T for peripheral and central collisions in $200A$ GeV ^{32}S + Au reactions. The final result, shown by the filled circles, has been obtained with the π^0 yield determined with all identified showers considered to be photons [photon identification method (A) above]. The variation of the final result with the photon identification method used in the π^0 yield extraction is shown by the open points for

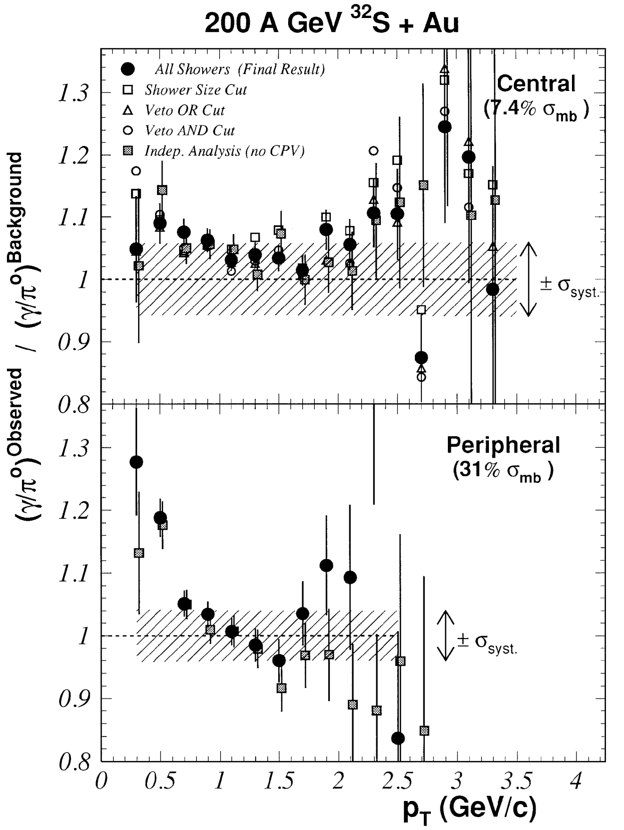

FIG. 1. The ratio $(\gamma/\pi^0)^{\rm obs}/(\gamma/\pi^0)^{\rm bkgd}$ as a function of transverse momentum for peripheral and central collisions of $200A$ GeV ^{32}S + Au. The errors on the data points (shown for the solid points only) indicate the statistical errors only. The shaded regions indicate the total estimated p_T-dependent systematic errors which bound the region corresponding to no photon excess.

the case of central collisions. This variation, in which the π^0 identification efficiency varies by more than a factor of 2, gives an indication of the level of systematic error which may be attributed to the π^0 yield extraction (see Table I). The total systematic error estimate is corroborated by the results of an independent complete γ and π^0 analysis shown by the light-shaded squares. This analysis was performed without the use of the CPV and featured independent methods and calculations of yields, efficiencies, and backgrounds. A fit to the final ratio with a constant value over the range $0.5 \leq p_T \leq 2.5$ GeV/c gives an average direct photon excess over background sources of 3.7% $\pm$ 1.0%(stat) $\pm$ 4.1(syst) for peripheral collisions and an excess of 5.0% $\pm$ 0.8%(stat) $\pm$ 5.8%(syst) for central collisions. These data are on average consistent within 1σ with no direct photon excess in both peripheral and central collisions. The larger statistical errors and smaller p_T coverage for the peripheral event class is a result of the much lower photon multiplicity. The difference between the preliminary WA80 result [3] and the present, final result is attributed to the above noted difficulties in the π^0 yield extraction.

The preliminary WA80 direct photon result generated a great deal of theoretical attention with various hydrodynamical model calculations [4–8]. Most of the model calculations were able to fit the preliminary WA80 photon excess yield under various, rather standard QGP formation scenarios [5–8]. Calculations were also presented for scenarios in which a QGP did not form, and these overpredicted the observed excess photon yield [5,7] (the greater magnitude in non-QGP scenarios is due to the higher initial temperature resulting from the fewer degrees of freedom in the hadronic matter).

Both of these qualitative observations remain true in light of the final result. With knowledge of the measured excess photon yield, and using the statistical and systematic errors of the measurement summed quadratically, an upper limit can be calculated at each p_T for the excess photon yield per event. Upper limits, at the 90% confidence level, on the invariant yield of excess photons per central ^{32}S + Au collision are shown in Fig. 2. These limits are similar in magnitude to the excess photon yields reported in the preliminary analysis; accordingly, the theoretical predictions of the scenarios with QGP formation remain consistent with the final upper limits, while the predictions of the scenarios without QGP formation, that is, with few hadronic degrees of freedom, remain ruled out by the final upper limits.

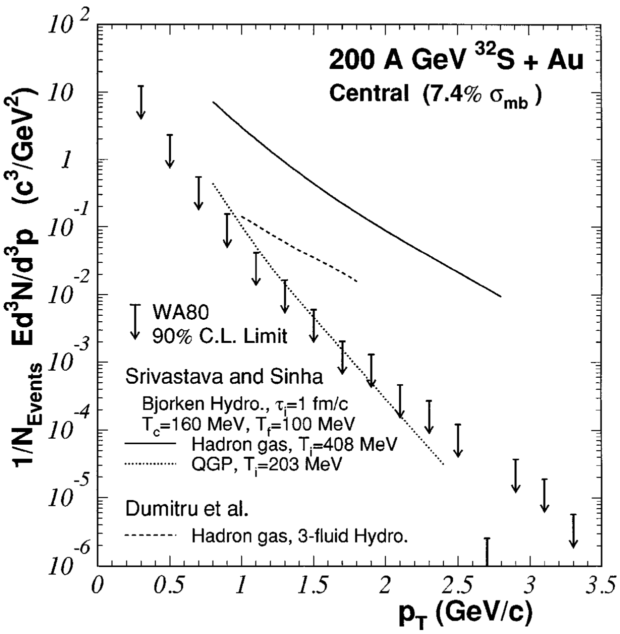

FIG. 2. Upper limits at the 90% confidence level on the invariant excess photon yield per event for the 7.4% σ_{mb} most central collisions of 200A GeV ^{32}S + Au. The solid curve is the calculated thermal photon production expected from a hot hadron gas taken from Ref. [5]. The dashed curve is the result of a similar hadron gas calculation taken from Ref. [7]. The dotted curve is the calculated thermal photon production expected in the case of a QGP formation also taken from Ref. [5].

This can be seen in Fig. 2 where the upper limit data are compared with the calculations of Ref. [5] for both the QGP and pure hadron gas scenarios, and with the pure hadron gas calculations of [7]. While no prediction for direct photon production can be considered definitive at the present time, the present upper limits on direct photon production rule out a simple thermal hadron gas description of the ^{32}S + Au collision within the context of these particular model calculations. It will be important to compare the upper limits with predictions of nonthermal models such as cascade calculations.

This work was supported jointly by the German BMFT and DFG, the U.S. DOE, the Swedish NFR, the Humboldt Foundation, the International Science Foundation under Contract No. N8Y000, the INTAS under Contract No. INTAS-93-2773, and ORISE. ORNL is managed by Lockheed Martin Energy Systems under Contract No. DE-AC05-84OR21400 with the U.S. Department of Energy.

*Deceased.

[1] See, for example, P. V. Ruuskanen, Nucl. Phys. **A544**, 169c (1992); J. Kapusta, Nucl. Phys. **A566**, 45c (1994), and references therein.
[2] R. Albrecht *et al.*, Z. Phys. C **51**, 1 (1991).
[3] R. Santo *et al.*, Nucl. Phys. **A566**, 61c (1994).
[4] E. V. Shuryak and L. Xiong, Phys. Lett. B **333**, 316 (1994).
[5] D. K. Srivastava and B. Sinha, Phys. Rev. Lett. **73**, 2421 (1994).
[6] J. J. Neumann, D. Siebert, and G. Fai, Phys. Rev. C **51**, 1460 (1995).
[7] A. Dumitru, U. Katscher, J. A. Maruhn, H. Stöcker, W. Greiner, and D. H. Rischke, Phys. Rev. C **51**, 2166 (1995).
[8] N. Arbex, U. Ornik, M. Plümer, A. Timmermann, and R. M. Weiner, Phys. Lett. B **354**, 307 (1995).
[9] R. Albrecht *et al.*, Phys. Lett. B **361**, 14 (1995).
[10] F. Berger *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **321**, 152 (1992).
[11] H. Baumeister *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **292**, 81 (1990).
[12] R. Albrecht *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **276**, 131 (1989).
[13] T. C. Awes *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **279**, 497 (1989).
[14] G. Hölker, Doctoral thesis, University of Münster, 1993.
[15] G. Clewing, Doctoral thesis, University of Münster, 1993.