MEASUREMENT OF DIRECT PHOTONS
IN 200-A GeV $^{32}\text{S}+\text{Au}$ COLLISIONS

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Presented for the WA80 Collaboration

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Two years ago at the 10th Winter Workshop on Nuclear Dynamics, we reported preliminary results from our measurements of photons in reactions of 200-A GeV ^{32}S ions with Au nuclei.¹ The results had been presented earlier at Quark Matter '93.² For central collisions we reported a small, but statistically significant, excess of photons over those that can be accounted for by the two-photon decay branches of π^0 and η mesons and by the small photon contributions from other radiative decays. This paper is, in a sense, a sequel to the 1994 presentation. Here we present the final WA80 single "direct" photon results,³ and we discuss their implications for various theoretical calculations.

As is pointed out frequently, photons, because of their low interaction probability, are considered to be a very promising probe suitable for studies of the early phases of hot and dense matter produced in relativistic nucleus-nucleus collisions. In particular, directly-radiated single photons may reflect the thermal properties of hot and dense matter, whether it be a hadron gas, a quark-gluon plasma (QGP), or a mixture of both. The possibility that photons are radiated from the QGP had been considered as early as 1978.⁴ Expected contributions to the observed photon yield from the QGP would very probably include $q-\bar{q}$ annihilation and the QCD equivalent of the Compton process in which a quark interacts with a gluon to produce a photon.

It was pointed out only relatively recently that a hot hadron gas is expected to radiate photons with emission rates that are similar to those that are expected from a QGP.⁵ The dominant production mechanisms in a hot hadron gas are expected to be $\pi^+\pi^- \rightarrow \rho\gamma$ and $\pi\rho \rightarrow \pi\gamma$, with a further increase in the production rate in the latter case due to the formation of the intermediate broad A_1 (1260) resonance.⁶ The pion annihilation mechanism is expected to dominate below about $p_T = 0.7$ GeV while the $\pi-\rho$ channel dominates at higher values of transverse momentum. Since the mean free path of the produced photons is considerably larger than the size of the nuclear volume associated with the reactions, photons produced during all stages of the reaction will

be observed, and should the QGP be formed, the total yield will be the result of time integration over three phase regions: pure QGP, mixed QGP-hadron phase, and pure hadron-gas phase.

In a thermalized system, when attempts are made to estimate contributions to the observed photon yield from the QGP, on the one hand, and from the hadron gas, on the other hand, it is useful to consider the number of degrees of freedom involved in each case. Given a fixed energy density produced in a given collision, a higher temperature is attained in a thermalized system that has a lower number of degrees of freedom. For a pure pion gas consisting only of bosons, the total number of degrees of freedom is 3, due to the isospin involved. In the case of the QGP, considering spin/polarization, isospin, and color, the number of degrees of freedom is 12 for the quarks and 16 for gluons. This large difference in the total number of degrees of freedom involved in the two cases leads to very different predictions for temperatures of thermalized systems and, hence, to the predicted, resulting photon yields. Unfortunately, whether the photons are estimated to originate from the QGP or from a hadron gas, their yield is predicted to be low relative to the yield of photons resulting from the decay of copiously-produced hadrons such as π^0 and η . This makes reliable measurements of direct photons extremely difficult. Of course, a hadron gas will not consist only of pions. Other hadrons and resonances need to be taken into account. However, even when these are considered, the predicted temperatures, and hence the photon yields, associated with hadron-gas scenarios tend to be significantly higher than those associated with possible QGP production.

There are, generally speaking, three experimental approaches to the determination of direct-photon yields. In the first, sometimes used in hadron-hadron reactions, a search is made for isolated photons that do not have a partner identified as resulting from hadron decay (e.g., from π^0 or η). This method requires low multiplicities and wide experimental coverage. It is not applicable to the high-multiplicity environment encountered in nucleus-nucleus collisions. An alternative approach is the measurement of a quantity that is related to the inclusive photon yield (e.g., conversion electrons) combined with model-dependent estimates of photons resulting from hadronic decays. This approach suffers from large uncertainties associated with the model assumptions. We have chosen a third approach which is appropriate for high-multiplicity environments and in which model assumptions are minimized. In our method we measure p_T spectra of identified photons simultaneously with the p_T spectra of π^0 and η mesons, which are the primary sources of decay photons. We then obtain the direct-photon yield on a statistical basis, as a function of p_T , by comparing the total photon yield to that which can be attributed to all long-lived decays. While the analysis of the data is very complicated and requires numerous corrections and careful estimates of systematic errors, it does lead to results that are sensitive at the 5% level of inclusive photons.

The WA80 experimental setup was described earlier.^{1,2} The photon measurement was performed with a finely-segmented electromagnetic calorimeter consisting of 3798 lead-glass modules. The detector coverage ranged from one-tenth to one-half of ϕ in the rapidity range between 2.1 and 2.9. Two layers of a streamer tube charged-particle veto (CPV) detector were located immediately in front of the lead-glass array.

The preliminary WA80 S+Au results presented earlier^{1,2} showed no significant excess of observed photons over those that can be accounted for by decays of known hadrons in peripheral collisions, while an excess at about the 2σ level was observed in central collisions. The preliminary results were presented in the form of plots of γ/π^0 ratios as a function of the transverse momentum (see, for example, Fig. 6 of Ref. 1

on page 125). The data as depicted in this form appeared to be of little interest to the theory community. However, when the data were presented at an informal meeting in the form of a p_T spectrum of the excess photons, theoretical interest picked up immediately and, within a period of less than two years, five papers appeared in which calculations were compared to the preliminary WA80 results.⁷⁻¹¹ The calculations involved essentially standard thermal-model QGP formation assumptions, and comparisons were made for various scenarios involving QGP formation, hadron gas formation, or a combination of both, including, in some cases, contributions from a mixed QGP-hadron gas phase. In general, scenarios in which a QGP did not form and in which photons were radiated only from a hadron gas led to overpredictions of the photon excess, as can be expected on the basis of the “degrees-of-freedom” arguments presented above.

The surge of theoretical interest, together with the difficulties associated with the extraction of the small direct photon emission component from data that are dominated by expected background photons originating from hadronic decays, has led to the decision to reanalyze the data by a WA80 team that was not intimately involved with the original analysis. As was mentioned above, an important feature of the WA80 measurements is that π^0 and η yields are obtained simultaneously with the inclusive photon yield, γ^{obs} , in the same p_T and rapidity region for each event class considered. This leads to a minimization of systematic errors resulting from the known centrality dependence of the meson p_T spectra. The single photon excess is determined, in principle, on a statistical basis from $\gamma^{excess} = \gamma^{obs} - \gamma^{bgd}$, where γ^{bgd} is calculated based on the measured π^0 and η yields. (A small contribution of the order of 2% due to photons originating from other radiative decays is estimated based on m_T scaling, which has been shown to hold for π^0 and η mesons^{1,12}) in the reactions considered here. In practice, however, results are usually presented in the form ratios $(\gamma/\pi^0)^{obs}$ and $(\gamma/\pi^0)^{bgd}$, since these ratios are less sensitive to systematic errors. Here we go a step further and present results in terms of the ratio of ratios, $(\gamma/\pi^0)^{obs}/(\gamma/\pi^0)^{bgd}$, which gives the fraction of photons observed relative to the expected decay background. This ratio will have a value of 1 if there are no excess photons. It has the advantages that both statistical and systematic errors are approximately constant over the entire p_T region and that systematic errors arising from acceptance corrections are minimized.

Due to the relatively low expected yield of direct photons, very accurate estimates of systematic errors are required. In many cases, the available data themselves can be used for systematic error estimates. Thus, for example, evaluation of the energy-dependence of the π^0 mass peak leads to estimates of energy nonlinearity. Another approach is to carry out the analysis as a function of different criteria and then compare the results to each other. This was done in the crucial case of photon identification, where different criteria lead to significantly different photon and π^0 identification efficiencies and to different background corrections. In order to determine which observed separated showers in the WA80 lead-glass detector are due to impinging photons, the following criteria of varying degree of restriction were applied: all observed showers; only showers with small lateral profile; only showers without an overlapping hit in either of the two charged-particle veto (CPV) layers located in front of the lead-glass array; and only showers without an overlapping hit in both CPV layers. In a consistent analysis, all of the above identification methods should give the same result, and the variation of the results gives an indication of systematic errors associated with both the single-photon and the π^0 yield determinations.

Table 1. Various sources of systematic error in the WA80 200-A GeV $^{32}\text{S}+\text{Au}$ direct photon analysis specified as a percentage of $(\gamma/\pi^0)^{\text{obs}}/(\gamma/\pi^0)^{\text{bgd}}$. The dependence of the errors on p_T is indicated.

p_T range (defined below):	Centrality: Peripheral collisions (31% σ_{mb})		Central collisions (7.4% σ_{mb})	
	a	b	a	b
Source of error				
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 ^c	0.5	0.5	0.5	0.5
Energy nonlinearity ^c	2.0	1.0	2.0	1.0
Binning effects ^c	1.0-0.0	0.0	1.0-0.0	0.0
Charged vs. neutral shower separation ^c	1.0	1.0	1.0	1.0
γ conversion correction ^c	1.0	1.0	1.0	1.0
Neutrons	1.5	0.5	1.5	0.5
Other neutrals, e.g., $\bar{n}$, 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 $p_T < 1.5$ GeV/c

^b $p_T > 1.5$ GeV/c

^cCentrality independent

A list of all known sources of systematic error in the determination of the direct-photon yield is given in Table 1 for peripheral and central collisions and for two different regions of p_T . The errors are expressed as a percentage of $(\gamma/\pi^0)^{\text{obs}}/(\gamma/\pi^0)^{\text{bgd}}$. Note that the largest systematic errors are associated with the determination of the π^0 yield and efficiency. This yield extraction is particularly difficult since the large, total multiplicity leads to centrality-dependent modifications of the π^0 mass peak due to shower overlap and to very unfavorable (as low as 0.1) peak-to-background ratios resulting from the huge two-photon combinatorial background.

The ratio $(\gamma/\pi^0)^{\text{obs}}/(\gamma/\pi^0)^{\text{bgd}}$ is shown in Fig. 1 as a function of p_T for peripheral and central collisions. The final result was obtained with the π^0 yield determined on the assumption that all identified showers are due to photons and is depicted by filled circles. Results of analyses using other criteria (see above) are shown by means of open symbols. The scatter of the points provides an indication of the level of systematic errors that can be attributed to the π^0 yield extraction. A further indication of systematic errors is provided by yet another independent analysis which was carried out without making use of the CPV data and in which independent methods were used to extract yields, efficiencies, and backgrounds. Results of this analysis are shown in Fig. 1 by means of light-shaded squares. A fit to the final ratios with a constant value over the range $0.5 \text{ GeV/c} \leq p_T \leq 2.5 \text{ GeV/c}$ gives an average photon excess over background sources of $3.7\% \pm 1.0\%$ (statistical) $\pm 4.1\%$ (systematic) for peripheral collisions and $5.0\% \pm 0.8$ (statistical) $\pm 5.8\%$ (systematic) for central collisions. This is consistent (within 1σ) with the absence of photon excess in both central and peripheral collisions. The difference between this final result and the preliminary results presented earlier^{1,2} is due primarily to the difficulties associated with the determination of the π^0 yields.

To facilitate comparisons with earlier theoretical calculations, we have deduced from our data, as a function of p_T , upper limits at the 90% confidence level on the

200 A GeV $^{32}\text{S} + \text{Au}$

Figure 1. The ratio $(\gamma/\pi^0)^{\text{obs}}/(\gamma/\pi^0)^{\text{bgd}}$ as a function of transverse momentum for peripheral and central collisions of 200-A GeV $^{32}\text{S} + \text{Au}$. 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.

invariant yield of excess photons per central $^{32}\text{S}+\text{Au}$ collision. The level of these limits is similar to the excess photon yield reported in the preliminary analysis, and the limit results constitute, in themselves, an important finding of WA80. The upper limits are shown in Fig. 2 by means of arrows, together with the calculations of Srivastava and Sinha⁸ and of Dumitru et al.¹⁰ The comparisons with our preliminary data featured in Ref. 8 attracted a great deal of popular attention. For example, an article entitled "Smashed Atoms Recreate Quark-Gluon Soup of Big Bang" appeared in the October 29, 1994, issue of *The New Scientist*. Such claims are clearly exaggerated. The main point of Srivastava and Sinha was that if only a hadron gas is formed in S+Au central collisions, then the limited number of degrees of freedom leads to a very high initial temperature (about 400 MeV). This, in turn, results in a predicted photon yield that is far greater than that of our preliminary analysis. On the other hand, a good fit to the preliminary data is obtained on the assumption that the system is initially formed in the QGP phase (at an initial temperature of about 200 MeV) and that it then expands, cools, and undergoes a first-order phase transition to a hadron gas at a critical temperature of 160 MeV, followed by freeze-out at 100 MeV. It can be seen in Fig. 2 that this conclusion remains unchanged when the comparison is made to our upper limits on direct photon production. The dotted curve depicting the QGP plus hadron gas scenario is consistent with our results, while the solid curve of the hadron gas scenario with no phase transition far exceeds the experimental upper limits.

Of the published theoretical calculations, those of Dumitru et al.¹⁰ are the most comprehensive. Addressing issues of dynamical evolution of the system, the authors used a three-fluid hydrodynamical model and were able to reproduce the rapidity distributions of negatively-charged hadrons at CERN/SPS energies as well as our transverse momentum distributions of neutral pions from central S+Au collisions at 200-A GeV. These additional comparisons with experimental results add credibility to their calculated thermal photon spectrum which is shown by the dashed line in Fig. 2 for the case of no phase transition. It is seen that this calculation also lies significantly above our upper limits. In contrast, the calculation of Ref. 10 in which a phase transition (possibly to a QGP) is assumed is consistent with our limits.

Some of the hadron-gas scenarios of Refs. 7-11 have been criticized as being unrealistic due to the restricted number of degrees of freedom that they consider. This and other related issues, were discussed recently at a meeting held at the Institute for Nuclear Theory at the University of Washington in Seattle, where our data were presented together with details of the analysis procedures used.¹³ Several direct-photon production calculations were presented at the meeting in their preliminary stages, indicating continued interest in direct-photon measurements. Our upper-limit results provide an important benchmark for these efforts. Particularly, in a thermal scenario, they place an upper limit on the temperature that may have been attained in central collisions. Future comparisons of our photon-production limits to photon production estimates based on nonthermal models, such as cascade calculations, will be of great interest.

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Figure 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 200-A GeV $^{32}\text{S}+\text{Au}$. The solid curve is the calculated thermal photon production expected from a hot hadron gas taken from Ref. 8. The dashed curve is the result of a similar hadron gas calculation taken from Ref. 10. The dotted curve is the calculated thermal photon production expected in the case of a QGP formation also taken from Ref. 8.

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