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Unique large thermal source of real and virtual photons in the reactions Pb(158*A* GeV) + Pb, Au

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The data of direct single-photon measurements of the WA98 Collaboration in the reaction Pb(158*A* GeV) + Pb are analyzed within a thermal model with a minimum number of parameters adjusted to the dilepton data obtained by the CERES and NA50 Collaborations in the reactions Pb(158*A* GeV) + Au, Pb. The agreement of our model with the WA98 data points to a unique large thermal source emitting electromagnetic radiation is observable in both the real and virtual photon channels.

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Direct real and virtual photons are now widely considered as very important penetrating probes of the early, hot and dense stage of relativistic heavy-ion collisions (see Ref. [1] for a recent survey). Efforts [2–4] have been devoted recently to understand the dielectron spectra measured by the CERES Collaboration in the reaction Pb(158*A* GeV) + Au in the low invariant mass region [5] and the dimuon spectra measured by the NA50 Collaboration in the reaction Pb(158*A* GeV) + Pb in the intermediate mass region [6]. Both experiments point to a significant excess of dileptons above the conventional sources such as electromagnetic decays of light hadrons (resulting in the hadronic cocktail), and correlated semileptonic decays of open charm mesons, and the Drell-Yan process. It is commonly believed that, in particular, the CERES data, obtained with lead and sulfur projectiles, could indicate a drastic change of the properties of hadrons, mainly the ρ meson, in a hot and dense surrounding hadronic medium [1]. For instance, transport simulations [7,8] including in-medium modifications of the light vector meson masses and widths are found to account for the excess of dielectrons. At the same time ‘‘traditional’’ hydrodynamical calculations [9], even when supplemented by the in-medium effects, give a dilepton yield which appears to be below the experimental data in the most important invariant mass region, $0.4\ \text{GeV} < M < 0.6\ \text{GeV}$. Only if one employs chemical off-equilibrium effects, e.g., parametrized by a finite pion chemical potential [10], the agreement of the hydrodynamical model calculations with data can be improved [2].

In a recent analysis [3,4] we proposed a model with a minimum set of parameters, which describes at the same time the CERES and NA50 dilepton data by a thermal source. In spite of its schematic character, the model is based on the nontrivial observation, made recently as a result of rather involved evaluations of the properties of hadrons near the chiral symmetry restoration, that the dilepton emission rate from a hadron gas at given temperature is fairly well described by the quark-antiquark annihilation rate at the same temperature in a wide range of invariant masses extending to small values [1]. This is called a ‘‘duality’’ of the hadronic and quark-gluon degrees of freedom in describing the emissivity of strongly interacting matter. Such a simplification makes it possible to parametrize the thermal source by a Boltzmann-like exponential function with effective temperature T_{eff} and a normalization factor N_{eff} which reflects the space-time volume occupied by the thermal source [4]. The most remarkable result of such a parametrization is that the dilepton spectra in both the low-mass region, as measured by the CERES Collaboration, and the intermediate-mass region, as accessible to the NA50 Collaboration, can be well described by the two unique parameters T_{eff} and N_{eff}. Also the transverse momentum spectra are well described [3,4]. This clearly indicates a common thermal source seen in different phase space regions and different dilepton channels.

In the present Brief Report we employ the above mentioned model for the thermal source to analyze the direct real photons in the reaction Pb(158*A* GeV) + Pb. In line with the hadron-quark ‘‘duality’’ we assume that deconfined and hadron matter shine equally bright in a temperature region centered around the critical temperature of chiral symmetry restoration.

An important information, which can be extracted from the photon spectra, is related to the transverse collective flow of matter. Unfortunately, the corresponding transverse momentum ($Q_\perp$) spectra of dileptons do not give so far such an opportunity, since in the large $Q_\perp$ region, where the flow effect is strongest, the total yield is dominated by the background contributions. The primary aim of the present note is to show that a thermal source, with parameters adjusted to the CERES and NA50 dilepton data, results in a photon spectrum which, when including the background, is in agreement with the data of the WA98 Collaboration [11] for the reaction Pb(158*A* GeV) + Pb.

For the emission of photons from a thermal source we employ the rate obtained in Ref. [12] for the free quark-gluon plasma at temperature T

$$E\frac{dN}{d^4x\,d^3p}=\frac{5}{9}\,\frac{\alpha\alpha_s}{2\pi^2}T^2\exp\left\{-\frac{pu}{T}\right\}\ln\left[1+\frac{\kappa(pu)}{\alpha_s T}\right], \qquad (1)$$

where $p^\mu=(E,\vec{p})=(p_\perp\cosh y, p_\perp\sinh y, \vec{p}_\perp)$ denotes the four-momentum of the photon with transverse momentum $p_\perp$ and rapidity y; u^μ is the four-velocity of the medium; the constant κ is according to Ref. [12] $\kappa=2.912/(4\pi)$. We use units with $\hbar=c=1$. The rate (1) takes into account the lowest order QCD processes, i.e., the $q\overline{q}$ annihilation and the Compton-like process. For the strong coupling strength we take $\alpha_s=0.3$. As shown in Ref. [12], at $T=200$ MeV this rate is very close to that of hadron matter when including a quite complete list of reactions of light mesons and the decays of vector mesons. This gives an additional hint for extending the mentioned hadron-quark ''duality'' to the real photon sector, at least for temperatures in the region of the chiral symmetry restoration. (At much higher temperature, the rate in Ref. [13] is probably more appropriate; see also Ref. [14].)

Since the thermal photon spectra are thought to be sensitive to the medium's flow we consider here the simplest case of a spherically symmetric expansion with velocity profile $v(r)=v_0 r/R(t)$, where r stands for the radial coordinate and $R(t)$ is the radius of the source, so that for a constant velocity parameter v_0 the size $R(t)$ increases linearly with time t. In line with our model of the thermal dilepton source [3,4] we replace the temperature by an effective average temperature T_{eff}, being constant. Within such an approximation one can factorize the space-time volume V_4 and the radiation emissivity. Performing the space-time integration in Eq. (1) one gets the photon spectrum as

$$E\frac{dN}{d^3p}=V_4\,F(E,T_{\mathrm{eff}},v_0), \tag{2}$$

$$F=\frac{5\,\alpha\,\alpha_s T_{\mathrm{eff}}^2}{12\pi^2}\int_0^1 ds\,s^2\int_{-1}^{+1}d\xi\,\mathrm{e}^{-A}\ln\left[1+\frac{\kappa}{\alpha_s}A\right], \tag{3}$$

where $A=p_\perp\cosh y\,(1-sv_0\xi)/T_{\mathrm{eff}}\sqrt{1-(sv_0)^2}$, and $V_4=(4\pi/3)\int dt\,R(t)^3$. Below we use the uniquely fixed parameters $T_{\mathrm{eff}}=170$ MeV and $V_4=N_{\mathrm{eff}}=3.3\times10^4$ fm^4, which have been previously adjusted [3,4] to the CERES and NA50 dilepton data.

We focus on the direct photon production assuming that the background, related to decays of secondary hadrons, is removed from the corresponding data [11]. To describe the spectra one also needs the contribution from hard initial processes, such as the Drell-Yan process in dilepton production, which is expected to dominate in the high-$p_\perp$ region. The hard photon yield is generated in our study by the event generator PYTHIA [15] with structure functions MRS $D-'$, default cutoff parameter $\hat{p}_{\perp\,\mathrm{min}}=1$ GeV for photons, and intrinsic transverse parton momentum spread $\sqrt{\langle k_\perp^2\rangle}=0.8$ GeV, adjusted to the transverse momentum spectra of dileptons in the Drell-Yan region in Ref. [3]; otherwise the default switches are used. Higher order calculations are presented in [16], but we try to absorb them into an appropriate K factor.

To check the reliability of estimates of the hard component, we compare in Fig. 1 the PYTHIA results with the photon data obtained in pp collisions by the E704 Collaboration at $\sqrt{s}=19.4$ GeV [17] (left part) and by the UA6 Collaboration at $\sqrt{s}=24.3$ GeV [18] (right part). To reproduce the data one has to include the K factors of 3.2 (1.8) for $\sqrt{s}=19.4$ GeV ($\sqrt{s}=24.3$ GeV). As seen in Fig. 1, PYTHIA describes then well the data, i.e., the slopes of the spectra, which are in the high-$p_\perp$ region, $p_\perp>2.5$ GeV. This conclusion is important for the subsequent analysis of the photon data in heavy-ion collisions, where the absolute normalization of the hard production is *a priori* unknown. To avoid additional uncertainties, being related to less sharply constrained K factors on the pp level and possible energy dependences [19] and extrapolations via pA to the AA case, we adjust directly the PYTHIA results at $\sqrt{s}=17.3$ GeV to the high-$p_\perp$ tail of the WA98 data[1] (we consider here central events defined by 10% of the most central reactions from the minimum bias cross section using the transverse energy [11]).

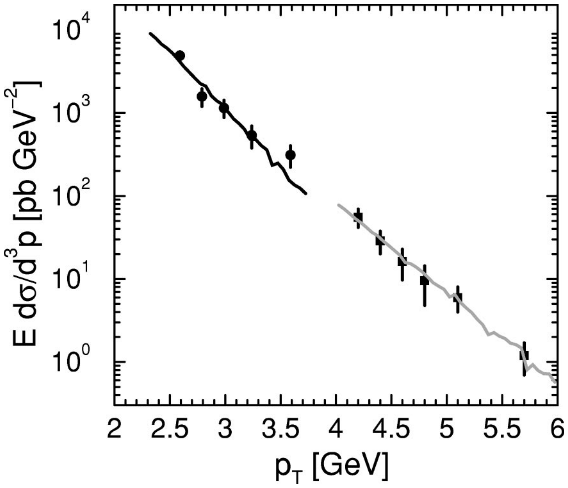

FIG. 1. Comparison of PYTHIA results with direct photon data in pp collisions. Left part: $\sqrt{s}=19.4$ GeV and E704 data (full dots) [17], right part: $\sqrt{s}$ = 24.3 GeV and UA6 data (full squares) [18].

The comparison of our thermal model yield plus the hard yield from PYTHIA with the WA98 data [11] is displayed in Fig. 2 for the case of neglecting the flow, i.e., $v_0=0$, and in Fig. 3 for the flow parameter $v_0=0.3$. [Similar to the PYTHIA calculations we simulate the thermal yield Eqs. (2), (3) by a Monte Carlo procedure and apply the detector acceptance [11] which is given by the pseudorapidity interval 2.35–2.95.] As seen in Fig. 2, the hard photon production process dominates in the high-$p_\perp$ region, since there we have adjusted the PYTHIA calculations to data. At $p_\perp<2.5$ GeV one can observe the increase of the experimental yield above the hard yield. In this region secondary processes become important. One has to stress, however, that in the region of not too large values of $p_\perp$ any hard photon production calculation based on perturbative QCD is not longer reliable. In particular, in the region of smaller $p_\perp$ the PYTHIA results become sensitive to the cutoff parameter $\hat{p}_{\perp\,\mathrm{min}}$.

As can be expected from Eq. (1), the contribution from the thermal source strongly depends on the transverse flow. The moderate value of $v_0=0.3$, used in Fig. 3, is consistent with the analysis of transverse hadron flow at kinetic decou-

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[1] Using the numbers of the second citation in Ref. [11] the resulting effective nuclear K factor is 7.

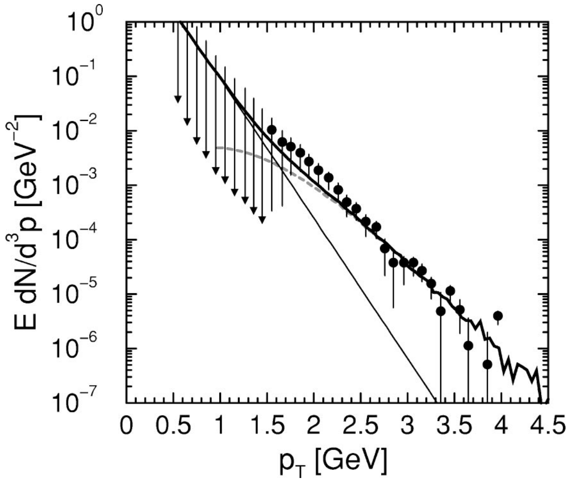

FIG. 2. Comparison of the thermal photon yield (thin curve, no transverse expansion) and the hard background (dashed curve) with the direct photon data [11] for the reaction Pb(158*A* GeV) + Pb. The solid line depicts the sum of the thermal and hard yields.

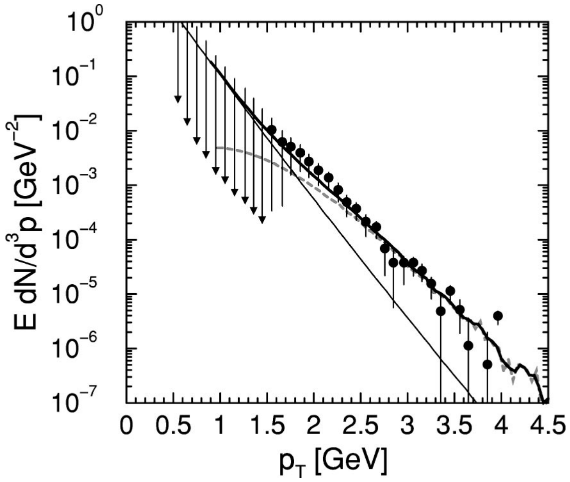

FIG. 3. As in Fig. 2, however, with transverse flow ($v_0=0.3$).

pling [20].[2] For such a flow parameter one finds good agreement with the data [11] when adding the thermal yield and the hard contribution (see Fig. 3).[3]

To make more firm conclusions on the role of thermal photons in Pb + Pb collisions at CERN-SPS energies, one needs a more reliable procedure to fix the hard background. Similarly to dileptons, an accurate adjustment of the hard rate at the high-$p_\perp$ tail requires an improvement of the data statistics. Notice that our present up scaling from PYTHIA simulations of *pp* collisions to heavy-ion data can be considered as an upper bound for the hard radiation. Nevertheless, a remarkable space is left for the secondary radiation.

An additional insight can be gained by an analysis of noncentral collisions which should allow a link to *pA* collisions, where also data are at hand [21]. This will be subject of a separate future study.

In summary we analyze the direct photon production in the reaction Pb(158*A* GeV) + Pb by using a model with a minimum parameter set, i.e., the effective temperature and the space-time volume of the thermal source, both ones adjusted to dilepton data in similar central reactions. The model employs the hadron-quark ''duality'' for the rate of electromagnetic radiation off matter. We have shown that our model, supplemented by the hard photon yield as described by PYTHIA, is in good agreement with the WA98 data. This result supports the assumption of an extended and long-living source of the electromagnetic radiation, which can be seen in both the real and virtual photon channels. The comparatively large value of the space-time factor V_4 in our model can be related to previous expectations on a long-living fireball [22] or a phase space overpopulation of hadrons [2,10].

It should be emphasized that our effective temperature parameter $T_{\text{eff}}=170$ MeV is in perfect agreement with the temperature parameter needed to describe hadron species ratios [23]. Since T_{eff} is to be considered as average of the temperature, one concludes that the electromagnetic probes indeed point to temperatures above the expected deconfinement temperature. This corroborates the expectation of exciting deconfined matter in central heavy-ion collisions already at CERN-SPS energies.

The photon spectra are shown to be useful in extracting information on transverse flow. For firm conclusions, however, the hard photon production processes must be reliably accessible. Our approach can be contrasted with attempts to interpret the data either without any hard contribution [14,24] or by the hard yield alone by tuning parameters. Transport approaches [25] should smoothly interpolate between these extreme cases.

We expect that the future analysis of the starting experiments at the relativistic heavy-ion collider RHIC at Brookhaven National Laboratory should deliver a higher value of T_{eff} since the estimated maximum temperatures will be significantly larger.

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[2] The quantity v_0, as T_{eff}, is to be understood as temporal average and, therefore, it should be smaller than the final hadron flow velocity at kinetic freeze-out. Indeed, values of $v_0 \geqslant 0.5$ would be incompatible with the photon data.

[3] An optimum description of the data is achieved by $v_0=0.4$. However, with respect to the uncertainty related to the hard background, we do not attempt such a fine tuning.

[1] R. Rapp and J. Wambach, hep-ph/9909229.
[2] R. Rapp and E.V. Shuryak, Phys. Lett. B **473**, 13 (2000).
[3] K. Gallmeister, B. Kämpfer, and O.P. Pavlenko, Phys. Lett. B **473**, 20 (2000).
[4] K. Gallmeister, B. Kämpfer, and O.P. Pavlenko, in 28th International Workshop on Gross Properties of Nuclei and Nuclear Excitation: Hadrons in Dense Matter, Hirschegg, Austria, 2000, edited by M. Buballa, W. Nörenberg, J. Wambach, and B.J. Schaefer (unpublished), p. 219, hep-ph/0001242.
[5] B. Lenkeit for the CERES Collaboration, Nucl. Phys. **A661**, 23c (1999); S. Esumi for the CERES Collaboration, Proceedings of the 15th Winter Workshop on Nuclear Dynamics, Park City, Utah, 1999 (unpublished).
[6] E. Scomaprin for the NA50 Collaboration, J. Phys. G **25**, 235c (1999); P. Bordalo for the NA50 Collaboration, Nucl. Phys. **A661**, 538c (1999).
[7] G.Q. Li, G.E. Brown, C.M. Ko, and H. Sorge, Nucl. Phys. **A611**, 539c (1996).
[8] W. Cassing and E.L. Bratkovskaya, Phys. Rep. **308**, 65 (1999).
[9] P. Houvinen and M. Prakash, Nucl. Phys. **A661**, 522c (1999); Phys. Lett. B **450**, 15 (1999).
[10] B. Kämpfer, P. Koch, and O.P. Pavlenko, Phys. Rev. C **49**, 1132 (1994).
[11] M.M. Aggarwal *et al.*, WA98 Collaboration, nucl-ex/0006007; nucl-ex/0006008.
[12] J.I. Kapusta, P. Lichard, and D. Seibert, Phys. Rev. D **44**, 2774 (1991).
[13] P. Aurenche, F. Gelis, H. Zakaret, and R. Kobes, Phys. Rev. D **58**, 085003 (1998).
[14] D.K. Srivastava and B.C. Sinha, Eur. Phys. J. C **12**, 109 (2000); D.K. Srivastava, *ibid.* **10**, 487 (1999).
[15] T. Sjöstrand, Comput. Phys. Commun. **82**, 74 (1994).
[16] C.Y. Wong and H. Wang, Phys. Rev. C **58**, 376 (1998); P. Aurenche, M. Fontannaz, J. Ph. Guillet, B. Kniehl, E. Pilon, and M. Werten, Eur. Phys. J. C **9**, 107 (1999).
[17] D. L. Adams *et al.*, E704 Collaboration, Phys. Lett. B **345**, 569 (1995).
[18] G. Ballocchi *et al.*, UA6 Collaboration, Phys. Lett. B **317**, 250 (1993).
[19] G.G. Barnaföldi, G. Fai, P. Levai, G. Papp, and Y. Zhang, nucl-th/0004066.
[20] B. Kämpfer, A. Peshier, O.P. Pavlenko, M. Hentschel, and G. Soff, J. Phys. G **23**, 2001 (1997); B. Kämpfer, hep-ph/9612336; B. Tomasik, U.A. Wiedemann, and U. Heinz, nucl-th/9907096.
[21] URL http://durpdg.dur.ac.uk/HEPDATA/photon1.html
[22] E.V. Shuryak, Nucl. Phys. **A661**, 119c (1999).
[23] J. Cleymans and K. Redlich, Phys. Rev. Lett. **81**, 5284 (1998); P. Braun-Munzinger, I. Heppe, and J. Stachel, Phys. Lett. B **465**, 15 (1999).
[24] D.K. Srivastava and B.C. Sinha, nucl-th/0006018; S. Sarkar, P. Roy, and J. Alam, Phys. Rev. C **60**, 054907 (1999).
[25] D.K. Srivastava and K. Geiger, Phys. Rev. C **58**, 1734 (1998); A. Dumitru, M. Bleicher, S.A. Bass, C. Spieles, L. Neise, H. Stöcker, and W. Greiner, *ibid.* **57**, 3271 (1998).