Radiation of single photons from Pb+Pb collisions at relativistic energies and the quark-hadron phase transition

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The production of single photons in Pb+Pb collisions at relativistic energies as measured by the WA98 experiment is analyzed. A quark-gluon plasma is assumed to be formed initially, which expands, cools, hadronizes, and undergoes freeze-out. A rich hadronic equation of state is used and the transverse expansion of the interacting system is taken into account. The recent estimates of photon production in quark matter (at the two-loop level) along with the dominant reactions in the hadronic matter leading to photons are used. About 50% of the single photons are seen to have a thermal origin. An addition of the thermal and prompt photons is seen to provide a very good description of the data. Most of the thermal photons having large transverse momenta arise from the quark matter, which contributes dominantly through the mechanism of annihilation of quarks with scattering, and which in turn is possible only in a hot and dense plasma of quarks and gluons. The results are thus compatible with the formation of quark-gluon plasma and the existence of this mechanism of the production of single photons.

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The search for quark-gluon plasma, which filled the early universe microseconds after the big bang and which may be present in the core of neutron stars, is one of the most notable collective efforts of the present day nuclear physics community. Its discovery will provide an important confirmation of the predictions of the statistical quantum chromodynamics (QCD) based on lattice calculations. It has been recognized for a long time [1] that electromagnetic radiations from relativistic heavy ion collisions in these experiments would be a definitive signature of the formation of a hot and dense plasma of quarks and gluons, consequent to a quark-hadron phase transition [1]. Once other signs of the quark-hadron transition, e.g., an enhanced production of strangeness, a suppression of J/ψ production, radiation of dileptons, etc., started to emerge [2], it was imperative that the more direct, yet much more difficult to isolate, signature of the hot and dense quark-gluon plasma, the single photons were identified. The WA98 experiment [3] has now reported observation of single photons in central Pb+Pb collisions at relativistic energies.

In the present work we show that these data are very well described if we assume that a quark-gluon plasma was formed in the collision.

In order to put our findings in a proper perspective, let us recall that the publication of the upper limit of the production of single photons in S+Au collisions at relativistic energies [4] by the WA80 experiment was preceded and followed by several papers [5,6] exploring their connection to the quark-hadron phase transition. An early work, by the present authors [5], reported that the data were consistent with a scenario where a quark-gluon plasma was formed at an initial time $\tau_0 \sim 1$ fm/c, which expanded and cooled, got into a mixed phase of quarks, gluons, and hadrons, and ultimately underwent a freeze-out from a state of hadronic gas consisting of π, ρ, ω, and η mesons. On the other hand, when the initial state was assumed to consist of (the same) hadrons, the resulting large initial temperature led to a much larger production of single photons, in gross violation of the upper limit.

A reanalysis of the WA80 data on single photons was reported recently [7] that incorporated two important developments in the field during the last few years, which are worth recalling. First, it was realized that the hadronic equation of state *must* be generalized to include all of the hadrons [8] (limited to $M < 2.5$ GeV, in practice). This was prompted and supported by the success of the thermal models in describing particle production in these collisions. This implied that the hadrons were in chemical equilibrium [9] at least at the time of (chemical) freeze-out. These hydrodynamical calculations have been shown to provide a very good explanation of the p_T spectra measured by the NA49 and NA44 experiments [10].

Second, an evaluation of the rate of single photon production from the quark matter to the order of two loops was reported recently by Aurenche *et al.* [11,12]. This had two quite important results: (i) a substantial contribution of the bremsstrahlung $[qq(g) \rightarrow qq(g)\gamma]$ process for all momenta in addition to the Compton $[q(\overline{q})g \rightarrow q(\overline{q})\gamma]$ plus annihilation $(q\overline{q} \rightarrow g\gamma)$ contributions included in the one-loop calculations available in the literature [13,14], and (ii) a large contribution by a new mechanism that corresponds to the annihilation of a quark (scattered from a quark or a gluon) by an antiquark. These new rates were shown [15] to lead to a considerable enhancement of the production of single photons at SPS, RHIC, and LHC energies, if the initial state is approximated as an equilibrated plasma.

It was also reported [7] that when allowances were made for the above considerations, the WA80 upper limit was still consistent with a quark-hadron phase transition, while a treatment without phase transition was untenable as it involved several hadrons/fm^3, at the initial time.

We add that there can be a production of high momentum single photons during the preequilibrium phase, when treated within the parton cascade model [16], from the fragmentation of timelike quarks ($q \rightarrow q\gamma$) produced in (semi)hard multiple scatterings [17].

The rate for the production of hard photons evaluated to one loop order using the effective theory based on resummation of hard thermal loops is given by [13,14]

$$E\frac{dN}{d^4x d^3k} = \frac{1}{2\pi^2}\alpha\alpha_s\left(\sum_f e_f^2\right)T^2 e^{-E/T}\ln\left(\frac{cE}{\alpha_s T}\right), \quad (1)$$

where the constant $c \approx 0.23$. The summation runs over the flavors of the quarks and e_f is their electric charge in units of charge of the electron. The rate of production of photons due to the bremsstrahlung processes evaluated by Aurenche *et al.* is given by

$$E\frac{dN}{d^4x d^3k} = \frac{8}{\pi^5}\alpha\alpha_s\left(\sum_f e_f^2\right)\frac{T^4}{E^2}e^{-E/T}(J_T - J_L)I(E,T), \quad (2)$$

and the expressions for J_T, J_L, and $I(E,T)$ can be found in Ref. [11].

And finally the dominant contribution of the $q\overline{q}$ annihilation with scattering obtained by Aurenche *et al.* is given by

$$E\frac{dN}{d^4x d^3k} = \frac{8}{3\pi^5}\alpha\alpha_s\left(\sum_f e_f^2\right)ETe^{-E/T}(J_T - J_L). \quad (3)$$

Note that all the three contributions turn out to be essentially of the order $\alpha\alpha_s$ [11]. It has been pointed out recently [12] that the values of J_T and J_L given originally by Aurenche *et al.* [11] are too large by a numerical factor of 4. We use the corrected values in the following.

The estimate of prompt photons is taken from the work of Wong and Wang [18] that employs the NLO pQCD along with the inclusion of the effects of intrinsic partonic momenta ($\langle k_T^2\rangle = 0.9$ GeV^2; see discussion later).

We assume that a chemically and thermally equilibrated quark-gluon plasma is produced in such collisions at the time τ_0 (see later), and use the isentropy condition [19]

$$\frac{2\pi^4}{45\zeta(3)}\frac{1}{A_T}\frac{dN}{dy} = 4aT_0^3\tau_0 \quad (4)$$

to estimate the initial temperature, where A_T is the transverse area.

We have taken the average particle rapidity density as 750 for the 10% most central Pb+Pb collisions at relativistic energy as measured in the experiment. We estimate the average number of participants for the corresponding range of impact parameters ($0 \leqslant b \leqslant 4.5$ fm) as about 380, compared to the maximum of 416 for a head-on collision. We thus use a mass number of 190 to get the radius of the transverse area of the colliding system and neglect its deviations from azimuthal symmetry, for simplicity. As this deviation, measured in terms of the number of participants, is marginal ($<9\%$) we expect the error involved to be small. We also recall that the azimuthal flow is minimal for central collisions.

We take $a = 42.25\pi^2/90$ for a plasma of massless quarks (u, d, and s) and gluons, where we have put the number of flavors as ≈ 2.5 to account for the mass of the strange quarks. We now use Eq. (4) to estimate the (average) initial temperature, with the additional assumption of a rapid thermalization [20] so that the formation time is decided by the uncertainty relation and $\tau_0 = 1/3T_0$. This T_0 is then used to get the (average) initial energy density.

It is important to have a proper initial energy density profile as it affects the hydrodynamic developments by introducing additional gradients. We assume it to follow the so-called "wounded-nucleon" distribution, which for central collision of identical nuclei leads to

$$\epsilon(\tau_0, r) \propto \int_{-\infty}^{\infty}\rho(\sqrt{r^2+z^2})dz, \quad (5)$$

where ρ is the (Woods-Saxon) distribution of nucleons in a nucleus having a mass number of 190 and r is the transverse distance. This is prompted by the experimental observation that transverse energy deposited in these collisions scales with the number of participants. The normalization in the above is determined from a numerical integration so that

$$A_T\epsilon_0 = \int 2\pi r\epsilon(r)dr. \quad (6)$$

We further assume that the phase transition takes place at $T = 180$ MeV and the freeze-out takes place at 120 MeV. This value of the critical temperature is motivated by the recent lattice QCD results that give values of about 170–190 MeV [21], and the thermal model analyses of hadronic ratios which suggest that the chemical freeze-out in such collisions takes place at about 170 MeV. (A recent analysis by Becattini *et al.* yields a value of 181.3 ± 10.3 MeV [9] for the chemical freeze-out temperature.) The phase transition should necessarily take place at a higher temperature.

The rates for the hadronic matter have been obtained [13] from a two-loop approximation of the photon self-energy using a model where π-ρ interactions have been included. The contribution of the A_1 resonance is also included according to the suggestions of Xiong *et al.* [22]. The relevant hydrodynamic equations are solved using the procedure [23] discussed earlier and an integration over history of evolution is performed [8].

In Fig. 1 we show our results. The dashed curve gives the contribution of the quark matter and the solid curve gives the sum of the contributions of the quark matter and the hadronic matter. The NLO pQCD estimates for prompt photons pp are also given. We see that the thermal photons contribute to about 50% of the total yield of the single photons and that the sum of thermal and prompt photons provides a very good description to the data. We also note that at higher transverse momenta most of the thermal photons have their origin in the quark matter.

How sensitive are the results to the choice of our parameters? In Fig. 2, we show our results where we vary the transition temperature by ±20 MeV. It is seen that the results at higher k_T (which have their origin in earlier times)

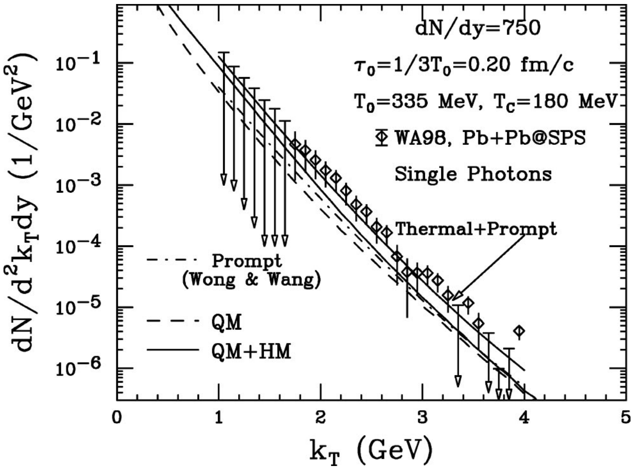

FIG. 1. Single photon production in Pb+Pb collision at relativistic energies. A chemically and thermally equilibrated quark-gluon plasma is assumed to be formed at $\tau_0 = 1/3T_0$ which expands, cools, enters into a mixed phase, and undergoes freeze-out from a hadronic phase. QM stands for radiations from the quark matter in the QGP phase and the mixed phase. HM likewise denotes the radiation from the hadronic matter in the mixed phase and the hadronic phase. Prompt photons are estimated using NLO *p* QCD with the inclusion of intrinsic k_T of partons (Wong and Wang [18]). The (tail) ends of the arrows denote the upper limit of the production at 90% confidence limit.

remain unaltered, though the yield at the lowest transverse momenta increases with the decrease in T_C.

The initial time τ_0 affects the results much more strongly, as increasing it lowers the initial temperature [Eq. (4)]. In Fig. 3(a) we show our results for $\tau_0 = 0.20$, 0.40, 0.60, 0.80, and 1 fm/c, corresponding to $T_0 = 335$, 265, 232, 210, and 196 MeV. A comparison of this figure with Fig. 1 shows that the data clearly favor a large initial temperature (and early thermalization). Recall that the hydrodynamic flow of all the systems (having same $dN/dy \sim T_0^3 \tau_0$) are known to be nearly identical at later times [23] and thus affect the hadronic data only marginally; see Fig. 3(b).

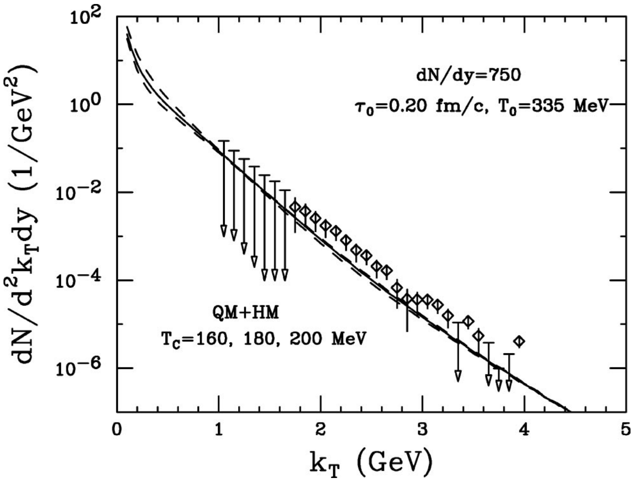

FIG. 2. The sensitivity of single photon spectrum to critical temperature. The solid curve is for $T_C = 180$ MeV, while the upper (lower) dashed curve is for 160 (200) MeV.

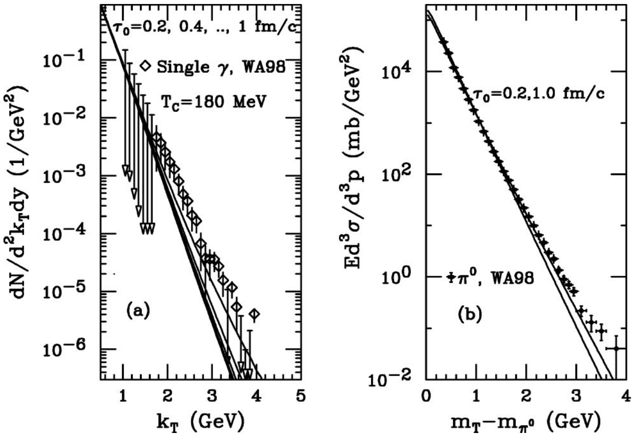

FIG. 3. The sensitivity of single photon (a) and pion spectrum [24] (b) to initial time (temperature). The curves, from top to bottom, correspond to initial times of 0.2, 0.4, 0.6, 0.8, and 1.0 fm/c for (a) and to 0.2 and 1.0 fm/c for (b).

A very important outcome of these results (Fig. 1) is that a very large part of the thermal component of the single photons is seen to have its origin in the quark-matter itself. Recall that the new (and dominant) mechanism of the annihilation of quarks with scattering, suggested by Aurenche *et al.*, is operative *only* if a hot and dense plasma is formed (see the detailed discussion in the Appendix in Ref. [11]). Thus these results are compatible the existence of this mechanism and the formation of quark-gluon plasma in such collisions.

Even though we realize that the creation of a hot (confined) hadronic matter in thermal and chemical equilibrium within $\tau_0 \approx 0.20$ fm/c, consequent to nuclear collision is highly unlikely [25], we estimate the initial temperature for such a system from Eq. (4) for the hadronic equation of state used here, as more than 260 MeV, when the hadronic density would be ≈ 10 hadrons/fm^3 [8]. We consider this very unphysical and unlikely. A larger formation time will give a much lower initial temperature and fail to explain the data.

How are we to understand the use of $\tau_0 = 1/3T_0 \approx 0.20$ fm/c here (see also [20]) against the canonical value of 1 fm/c, employed often? First, within the model used, this value is *favored* by the data (Fig. 3). Second, if a larger value of τ_0 is used, then an allowance should be made to supplement the predictions with an appropriate preequilibrium contribution (see e.g., Ref. [26]). Third, we note that the matter at $z=0$ starts interacting by $t = -R/\gamma \approx -0.7$ fm/c in the present case, when the two nuclei start touching. Thus by the lapse of $\tau = 0.2$ fm/c, the matter there has been under interaction for a time ~ 1 fm/c, which may be enough for the formation of the plasma.

Finally, a very important confirmation of our findings comes from the observations of Eskola *et al.* [27], that a saturation of partons signaling a complete filling up of the transverse area by colored quanta in collision of lead nuclei at SPS energies is indeed attained when the momentum transfer in partonic collisions is of the order of 1 GeV leading to a temperature ~ 300 MeV at $\tau_0 \sim 0.2$ fm/c.

We add that the model developed here provides a very good description [10] of the intermediate mass dilepton excess measured by the NA50 group.

Are we justified in making the assumption of a chemically equilibrated plasma, considering that indeed the predictions at the lower transverse momenta are close to the upper limits given by the experiment? This needs to be investigated (see Neumann *et al.* [6]) as also the effect of (likely) medium modification of hadron properties. The neglect of the baryochemical potential for the quark-gluon plasma (QGP) is perhaps justified as the net baryon to hadron ratio is quite small [28], especially in the region of the central rapidity. Finally, we may add that the photon rates used in these calculations are strictly valid only for $\alpha_s \ll 1$ and that the consequences of considering higher loops remains to be seen.

Before summarizing, let us return to the question of prompt photons. A detailed discussion on them is beyond the scope of this paper, and the debate on the reproducibility of single photons data in fixed target $pp(A)$ experiments is inconclusive. If we are to believe the results of Wong and Wang [18], which we have employed, then the prompt photons contribute about half of the total yield in the present work. As mentioned earlier, these results are obtained by using NLO p QCD predictions along with the inclusion of intrinsic momenta of partons.

The classic paper of Owens [29] discusses the need to account for the intrinsic transverse momenta of partons. However, that work also talks of the need to introduce a cutoff in Q^2, below which p QCD cannot be applied and to avoid singularities in the parton-parton matrix elements. This discussion is absent in Ref. [18,30]. Large enhancements can be obtained depending on the cutoffs employed and the $\langle k_T \rangle$ used. The extent to which these considerations will affect the results of Wong and Wang is not known.

We also recall the exhaustive work of Vogelsang and Whalley [31]; especially their Fig. 31, where the differences of *all* the pp data from NLO p QCD predictions are plotted. It is seen that while all the pp data for $\sqrt{s} > 23$ GeV are quantitatively explained by NLO p QCD, the one at 19.4 GeV is underpredicted by a factor of 4–5. If this trend is assumed to continue then at the relevant nucleon-nucleon energy of 17.3 GeV, this difference would mount to a factor $>10(!)$. The NLO p QCD analysis of these authors is also applied to $p+Be$ data at 31 GeV (by normalizing it to pp) and a very good description is obtained, while the same procedure underestimates the $p+C$ data at 19.4 GeV by a factor of 4–5. Several of these data have also been critically examined by Aurenche *et al.* [32] within NLO p QCD, who conclude that

(i) There is no need to include intrinsic momentum effects;

(ii) The perturbation theory becomes unstable at lower k_T when intrinsic momenta of partons is included; and

(iii) The data at lower energies are incompatible with those at higher energies, especially the $p+Be$ data.

Several other papers (see Ref. [32]) also discuss these aspects.

On the other hand the authors of Ref. [33] have studied the effect of the so-called p_T broadening (Cronin effect) in proton-nucleus collisions. The LO p QCD is used along with a K factor and an intrinsic $\langle k_T \rangle$ for the partons. The fact that the $p+Be$ data is explained reasonably well by Vogelsang and Whalley [31] using NLO p QCD, argued to have ‘‘incompatible’’ normalization by Aurenche *et al.* [32], and believed to require an intrinsic $\langle k_T \rangle$ for partons as well as Cronin broadening of the intrinsic momenta of partons [33] leaves the field open to diverse interpretations. From a purely empirical consideration also, it has been pointed out that [34] the lowest energy pp data for single photons are *not* consistent with the data at higher energies (and are too high).

In the light of the above, we take the view that the estimates of the prompt photons given by Wong and Wang [18], give the upper limit of these contributions.

Summarizing, we find that the single photons measured in the WA98 experiment are compatible with the formation of quark-gluon plasma in the collision and that most of thermal radiation at higher transverse momenta seems to come from the annihilation of quarks with scattering, which operates only if a plasma is formed. As expected, the slope of the spectrum provides a very good measure of the initial temperature reached in the collision.

This holds out the hope of a rich display of radiation of photons from the quark matter at RHIC and LHC energies in collisions involving heavy nuclei, as much larger temperatures are likely to be attained there. The long life of the QGP phase at LHC energies will make it sensitive to such details like the transverse flow (within the QGP phase itself), which will be of immense help in deciphering the properties of the quark-matter.

Note added. Further discussions. We would like to take this opportunity to comment on some papers that have been posted [35,30,36] on the e-print archives *after* this paper was originally submitted. This discussion is necessary in view of the important conclusions drawn in this work, which differs in detail with findings in these papers.

The authors of Ref. [35] have used a very simple model to parametrize the evolution of the plasma. A spherical (!) expansion of the plasma is envisaged that continues to radiate photons during the entire lifetime at a *fixed* (average, effective) temperature. While this may be useful to suggest that there *is* an additional production of photons, this approach is too simple to help us arrive at quantities like initial temperature, T_C, etc. Moreover as, at the relevant nucleon-nucleon energy ($\sqrt{s} = 17.3$ GeV) for the WA98 data under consideration, there is no pp data, these authors further scale the predictions of PYTHIA for pp (which required a K factor of 3.2 and intrinsic parton momentum for the E704 data at 19.4 GeV) to the WA98 data for $k_T > 2.5$ GeV. This fore closes any hope to get information about the origin of these photons by assigning them to hard QCD interactions among partons whose distribution is obtained from structure function.

The authors of Ref. [30] have used an early version of the transverse expansion code used in the present work, which was originally adopted from the work of Ruuskanen and coworkers [23]. The model uses an energy-density profile that is unform upto the transverse radius R, a hadronic gas that consists of only π, ρ, ω, η, and a_1 mesons and nucleons, and uses the method of effective number of degrees of freedom at each temperature. This hadronic matter will have a much smaller number of degrees of freedom at T_C, leading to a long lived mixed phase compared to the case of rich hadronic matter used in the present work. The overall life time of the system will then be larger, considerably enhancing the yields from the hadronic and the mixed phases. Thus one would need only a smaller contribution from the QGP phase to explain the data, as reported by these authors. It remains to be seen, how these results will behave when the a correction for the numerical factor of 4 [12] in rates given by Ref. [11] is made. Further, the method of temperature dependent number of degrees of freedom will lead to a speed of sound $c_s = 1/\sqrt{3}$ at all temperatures. A uniform energy density profile does not reflect the actual situation either, as it would follow wounded-nucleon distribution used in the present work.

Another aspect of this work is introduction of an *initial* transverse velocity. It is well known from the pioneering work of authors of Ref. [23] that the $\langle p_T \rangle$ of the produced particles can be arbitrarily increased if a strong initial transverse flow is assumed. A look at Fig. 3 of the present work also suggests that one can use a larger formation time (smaller initial temperature) and an initial flow to *arbitrarily* increase the large k_T production. The authors of Ref. [36] have also introduced a large initial transverse velocity.

However, it is known from the arguments of Ref. [23] that in a head-on collision of nuclei, introduction of initial transverse velocity is not physically justified and one expects that, with the exception of the outer surface, the produced matter would be transversely at rest. At the most one may expect that the initial flow may be stronger near the surface, which expands against the vacuum, there is no conceivable mechanism to provide a significant initial transverse collective motion, across the fluid.

The initial scattering among partons will produce quarks and gluons pointing in random directions. In any given volume element their momenta would be uniformly distributed in all directions, and rescatterings will then evolve a temperature and pressure. This temperature and pressure (gradient) will initiate a flow when the plasma starts expanding against the vacuum.

Both these works, Ref. [30,36], also include the LO p QCD predictions for the hard photons. While the authors of Ref. [30] include the intrinsic k_T as in the work of Ref. [18], they apparently do not use a K factor, though they use the LO p QCD. The authors of Ref. [36] use a K factor of 2 and find that they underestimate the pp data at 19 GeV by a factor of 7 (implying an effective K factor of $\sim 14(!)$ over the LO prediction).

We have commented that the initial conditions deduced here provide a quantitative description to the intermediate mass dilepton spectra measured by the NA50 group [10]. It is of interest to understand the origin of the differences in the initial conditions inferred by us and those by the authors of Ref. [37], who report an initial temperature of about 200 MeV at an initial time of ~ 1 fm/c. The fireball model used in Ref. [37], envisages a cylinder whose length and radius increase with time. The cylinder is assumed to be uniformly filled with plasma having temperature $T(t)$. We know for sure that the profile of the energy density produced in such nuclear collisions *cannot* be uniform, and this leads to additional gradients in the hydrodynamic evolution. The model also does not account for the fact that the speed of sound is large during the QGP phase, vanishingly small during the mixed-phase, and varying with temperature during the hadronic phase if a rich hadronic equation of state is used. Thus, for example, during the mixed phase their parameters a_z and a_T (which correspond to acceleration of the expanding surface) *must* vanish. Even though the parameters of the model are adjusted to give a transverse velocity equal to that deduced from particle spectra and a transverse size deduced from interferometry, it cannot be expected to adequately reflect the rich history of evolution of the plasma formed in nuclear collisions, and by extension, the initial conditions.

These simplifying assumptions provide that the contribution of the hadrons to radiations from the system is larger, necessitating only a small contribution from the QGP phase (and smaller initial temperature).

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