Emission of single photons, hadrons, and dileptons in $Pb + Pb$ collisions at CERN SPS and quark hadron phase transition

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The production of single photons in $Pb + Pb$ collisions at the CERN SPS as measured by the WA98 experiment is analysed. 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 two loop level) along with the dominant reactions in the hadronic matter leading to photons are used. About half of the radiated photons are seen to have a thermal origin. The same treatment and the initial conditions provide a very good description to hadronic spectra measured by several groups and the intermediate mass dileptons measured by the NA50 experiment, lending a strong support to the conclusion that quark gluon plasma has been formed in these collisions.

It has been recognised for a long time that electromagnetic radiations from relativistic heavy ion collisions 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. Once other signs of the quark-hadron transition, e.g., an enhanced production of strangeness, a suppression of $J/\psi$ production, radiation of dileptons, etc., started to emerge, 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 has now reported observation of single photons in central $Pb + Pb$ collisions at the CERN SPS.

In the present work we show that these data, along with the hadronic spectra measured by several groups and the intermediate mass dileptons measured by the NA50...
experiment are very well described if we assume that a quark-gluon plasma was formed in the collision.

Figure 1. Single photon production in \( Pb + Pb \) collision at the CERN SPS. QM stands for radiations from the quark matter in the QGP phase and the mixed phase, HM denotes the radiation from the hadronic matter in the mixed phase and the hadronic phase. Prompt photons are estimated using NLO pQCD with the inclusion of intrinsic \( k_T \) of partons (Wong and Wang [15]).

Figure 2. Transverse momentum spectra of neutral pions, protons, kaons and \( \Sigma + \Lambda \) in central collisions of lead nuclei at CERN SPS. The initial conditions used for all the figures are identical.

We incorporate two important improvements in our analysis. Firstly, the hadronic equation of state is generalized to include all of the hadrons [6] in the particle data book. Secondly, we use the rate of single photon production from the quark matter to the order of two-loops reported recently by Aurenche et al [7]. A recalculaition of these rates have been reported recently [8] and it has been claimed that the result of Aurenche et al. is too high by a numerical factor of 4. We use the corrected rates in what follows. The results presented during the conference used the former rates of Aurenche et al. (This affects only the Fig. 1.) For analysis of the dilepton production we use the exhaustive rate calculations of Ref. [9].

We assume that a chemically and thermally equilibrated quark-gluon plasma is produced in such these collisions at the time \( \tau_0 \), and use the isentropy condition [11]:

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

(1)

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
the CERN SPS energy as measured in the experiment. We use a mass number of 190 to account for non-zero impact parameter based on estimates of number of participants. The plasma is assumed to consist of massless quarks (u, d, and s) and gluons with the number of flavours as \( \approx 2.5 \) to account for the mass of the strange quarks. We assume a rapid thermalization \([12]\) so that the formation time is decided by the uncertainty relation and \( \tau_0 = 1/3T_0 \). The energy density profile is assumed to be proportional to the wounded nucleon distribution. We further assume that the phase transition takes place at \( T = 180 \) MeV and the freeze-out takes place at 120 MeV. The rates for the hadronic matter have been taken from Ref. \([10]\) and the contribution of the \( A_1 \) resonance is included according to the suggestions of Xiong et al \([13]\). The relevant hydrodynamic equations are solved using the procedure \([14]\) discussed earlier and an integration over history of evolution is performed \([6]\).

In Fig. 1 we show our results for single photons. 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 estimate for prompt photons, with the inclusion of intrinsic partonic momenta are also given \([15]\). We see that the thermal sources contribute about 50% of the single photons and that a very good description of the data is obtained when the thermal and the prompt sources are added. Consequences

Figure 3. The invariant mass distribution of dilepton production in NA50 experiment \([5]\).

Figure 4. The \( p_T \) distribution of dileptons produced in central collision of lead nuclei.
of variation of some of the parameters can be seen in Ref. [16]. The fit to pion spectra from the WA98 experiment [4], kaon and proton spectra from the NA44 experiment [2], and the \( \Lambda + \Sigma \) spectra from the NA49 experiment [3] are given in Fig. 2. The production of intermediate mass dileptons measured by the NA50 experiment is shown in Fig. 3. We see that the sum of the thermal and Drell-Yan contributions provides a good description to the experimental data. We add that we have used the procedure described in Ref. [17] to simulate the detector acceptance. We also add that the thermal production is quite identical to the enhanced production of charm decay estimated by the NA50 group to ‘explain’ this excess. The corresponding fit to the \( p_T \) spectrum is shown in Fig. 4. It should be noted that contrary to the findings of Ref. [17] most of the radiations in the present work comes from the quark matter itself. This difference is most likely due to the rich equation of state along with a sophisticated evolution mechanism for the plasma employed in the present work Ref. [18].

In brief, we have shown that a single set of initial conditions, which involve a quark gluon plasma in the initial state and envisage a quark-hadron phase transition during the evolution, are able to provide a consistent description to single photons, dileptons, and hadrons produced in central \( Pb + Pb \) collisions measured at the CERN SPS. This we feel, provides a very strong support to the claim that a quark gluon plasma is formed in these experiments.

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