A first order quark-hadron phase transition and SPS photon spectrum

Prashant Shukla

Nuclear Physics Division,

Bhabha Atomic Research Center, Mumbai 400085, India

Abstract

Different scenarios of a first order quark hadron phase transition arising from supercooling have been studied in a hydrodynamical model. Manifestations of these scenarios in the photon spectrum from Pb+Pb collision at SPS energy have been demonstrated. Possible imprints of these scenarios on the other measured data is also discussed.

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The ultra relativistic heavy ion collision experiments are performed with the aim to produce matter with very high energy density required to form quark gluon plasma (QGP). With this aim, Pb+Pb collision experiments at $\sqrt{s} = 17.6A$ GeV have been carried out at CERN SPS giving a variety of data on electromagnetic and hadronic observables [For a review see [1]]. The most interesting of these are the electromagnetic probes [2,3], which are sensitive to various stages of the evolution of the system and may contain the information on QGP formation. A considerable amount of theoretical work has been done to extract the information on QGP from these data [For review see [4,5]].

To explain the data with hydrodynamical models, one assumes that, QGP is formed with given initial conditions which then expands hydrodynamically till it reaches the critical temperature T_C for a first order quark-hadron phase transition. In the idealized Maxwell construction, the temperature of the system is held fixed at $T = T_C$ until the hadronization is completed. Thus, in turn one assume that the latent heat obtained by the phase transition compensates the temperature drop due to cooling. Such a picture has been widely used in literature while describing the electromagnetic signals (See e.g. [6]). This is a good approximation when the expansion time scales are far greater than the phase transition time scales as in the case of early universe. For the case of relativistic heavy ion collisions, there have been extensive studies of the space time evolution of QGP undergoing a first order phase transition by nucleation [7–10]. As a result of rapid expansion of the system, a substantial amount of supercooling is expected and the dynamics of quark hadron phase transition becomes quite different in heavy ion collisions as compared to that in early universe [9,11]. When the hydrodynamical equations are coupled with nucleation rate equation [12], the QGP is shown to supercool to a temperature T_S lower than T_C. The hadronization proceeds by thermal fluctuation from this metastable QGP to stable hadron phase. The system reheats due to the release of latent heat and approaches T_C as the hadronization proceeds. This also corresponds to an equilibrium situation where the latent heat generated goes into reheating the system.

In heavy ion collisions, the cooling time scales are comparable to the phase transition time scales, that gives rise to many interesting possibilities around T_C. It is possible for example, that QGP supercools to a temperature, at which the barrier between the metastable QGP and the stable hadron phase minima completely vanishes leading to a point of inflection at $T = T_{\text{spino}}$. This is known as spinodal instability [12]. In this case, the rapidly quenched system leaves the region of metastability and enters the highly unstable spinodal region before a substantial amount of nucleation begins. There is no metastable state from which one can not define the phase transition by thermal fluctuation. Alternatively, spinodal decomposition has been suggested as a possible mechanism of phase conversion for a rapidly expanding system of quarks and gluons [12–14]. This hadronization process is much faster than the nucleation and is also referred as explosive decomposition [15]. In this scenario, the QGP breaks up into small droplets of plasma in a non equilibrium way, which will form hadrons. It is unlikely for the system to undergo re-equilibration and thus it will freeze out at this point. Such a picture has been presented many times in the literature and it is referred as 'a fast shock like hadronization' in Refs. [16] and as 'a sudden hadronization scenario' in Ref. [17]. The signature of such a scenario will be very short life time [18] of the system measured through HBT data and should combine with no mass shift in ρ and ϕ etc. observed in dilepton spectrum and large departures of hadron spectrum from equilibrium distribution.

In case of nucleation, another possibility arises at the late stage of hadronization when most of the QGP volume has been converted to hadrons. The system can be considered in the form of hadron clusters and the small QGP bubbles. At such a point, fluctuation theory is not applicable for hadronization of remaining small fraction of QGP. Further hadronization by equilibrium processes stops here and the system may simply break up into fragments: hadronic clusters and small droplets of plasma which then form the final state hadrons. Such a possibility is presented in Ref. [10].

As all these scenarios exist in the literature, it is worthwhile to see their manifestation in the measured photon spectrum [2] which is the best probe of space time evolution of quark-gluon plasma (QGP) possibly produced in relativistic heavy-ion collisions. While a number of models have been proposed in context with photon data, the supercooling, which is an essential feature of first order phase transition has never been included to calculate photon spectrum. Here we concentrate mainly on this aspect and apply the most common set of parameters, equation of state and the expansion scenario for our calculations. We consider that a baryon free QGP is formed at some initial temperature $T_i = 211$ MeV and initial time $\tau_i = 0.8$ fm and starts cooling by Bjorken hydrodynamics. Transverse expansion is not taken into account considering short life time of the system. To get the equations of state, it is assumed that QGP is a massless 2 flavour parton gas and hadronic phase is a massless three pion gas. When the QGP cools to the critical temperature $T_C = 160$ MeV at $\tau_C = 1.83$ fm, we invoke following four scenario for the calculations:

1. Idealized Maxwell construction: The temperature of the system is held fixed at $T = T_C$

during hadronization. The hadronization completion time $\tau_h \sim 23$ fm can be simply calculated by entropy conservation. After this, the hadron gas cools to freeze out temperature $T_f = 145$ MeV at $\tau_f \sim 30$ fm. Such a calculation is shown by dashed line in Fig. 1.

2. Nucleation and supercooling scenario: At $T = T_C$, hydrodynamical equations are coupled with nucleation rate equations [12]. The QGP supercools to a temperature $T_S = 0.9 T_C$. The hadronization proceeds by thermal fluctuation from this metastable QGP phase to stable hadron phase. The system reheats due to the release of latent heat and approaches $T = T_C$ as the hadronization proceeds. When hadronization is completed, the hadron gas cools and freezes out at $\tau_f = 34$ fm. Such a calculation is shown by solid line in Fig. 1.

3. Spinodal decomposition followed by freeze out: QGP supercools to the temperature $T = T_S$, which is close to spinodal temperature [12] which can be calculated as

$$T_{\rm spino} = \left[\frac{B}{B + 27 V_b}\right]^{1/4} T_C, \qquad V_b = \frac{3\sigma}{16\xi}. \tag{1}$$

   For Bag constant $B^{1/4}$= 222 MeV, surface tension σ= 25 MeV/fm^2 and correlation length $\xi = 0.7$ fm, one can calculate $T_{\rm spino} = 0.894 T_C$, which is very close to the minimum temperature in supercooling. The QGP breaks up into small droplets of plasma, which will form hadrons coinciding with freeze out at temperature T_S and time $\tau_s = 2.93$ fm.

4. Fragmentation at late stage of hadronization followed by freeze out:

   In the nucleation scenario when most of the QGP volume has been converted to hadrons at time τ_p, the system breaks up into fragments: hadronic clusters and small droplets of plasma. The time τ_p is adjusted to reproduce the SPS data. This corresponds to 94 % hadronization at time $\tau_p = 15.5$ fm. This is also assumed to coincide with freeze out.

It is to be mentioned that, the same supercooling curve is used for scenario 2, 3 and 4. They differ only by implementation of freeze out at different times, due to different physical conditions.

The total thermal photon emission rate is given by the sum of corresponding rates $R_{\rm QGP}$ in the QGP and $R_{\rm hadron}$ in the hadron regions integrated over space time volume element $d^4x = \tau d\tau d\eta_f \pi R^2$ as

$$E\frac{dN}{d^3p} = \int_{\tau_i}^{\tau_f}\int_{-l}^{l}\left[(1-h(\tau))R_{\rm QGP}(T(\tau),\eta_f) + h(\tau)R_{\rm hadron}(T(\tau),\eta_f)\right] d\eta_f \tau d\tau \pi R^2. \qquad (2)$$

Here η_f is the fluid rapidity integrated from $-l$ to $+l$ ($l = 2.8$) and R is the size of colliding nuclei given by $R = 1.2\,A^{1/3}$, A=208. The temperature, $T(\tau)$ and the hadronic fraction, $h(\tau)$ are obtained as a function of time using the four scenarios mentioned above.

For $R_{\rm QGP}$ and $R_{\rm hadron}$, we use the parameterized forms given in Ref. [19]. The QGP rate corresponds to the photon production rate from an equilibrated 2 flavour QGP, calculated in perturbative thermal QCD. The contribution of prompt photons, produced in the initial scattering has been obtained by the PYTHIA calculations of Ref. [20] and are parameterized as

$$E\frac{dN}{d^3p} = \exp(a + bP_T + cP_T^2 + dP_T^3), \text{ with}$$
$$a = -5.9883,\ b = 2.0934,\ c = -1.6015,\ d = 0.1432. \qquad (3)$$

Figure 2 demonstrates how the thermal photon contributions due to different evolutions compare with SPS data (filled circles). The prompt photons (thick solid line) have been added in all calculations. The idealized Maxwell construction corresponds to the short dashed line. It exceeds the experimental limits in the low P_T region. The full nucleation and supercooling (scenario 2) corresponds to the middle dashed line which shows more photons in the low P_T region. This is due to the fact that the system has spent more time in region with temperature lower than T_C. The scenario (3) (long dashed line) looks the most improbable at SPS energies. The analysis of CERES dilepton data shows signatures of in-medium effects and mass shifts of ρ and ϕ mesons [21] supporting above conclusion.

From this figure (Fig. 2), scenario (4) (solid line) seems the most appropriate evolution scenario at SPS. The freeze out temperature is ~ 160 MeV. This gives a life time of ~ 15 fm which is about half of the life time given by the idealized Maxwell construction. It should be judged against the HBT data, which show short duration of particle emission as well as short life time of the system before freeze out [22]. The measured hadron yields must increase at higher momentum over the value obtained from the equilibrium distributions, due to the hadrons coming from the QGP droplets after freeze out. Notably, in the analysis of SPS hadron spectrum in Ref. [23], it was observed that there are more hyperons than expected, which could result from the picture presented above.

We would like to mention that it is also possible to reproduce the SPS photon data by different models as reviewed in [4,5], some of which we discuss in the following: Taking the scenario 1 as baseline, the photon data shows a much flatter distribution or in other words a larger slope. One can achieve a flatter distribution by the scenario 1 by different means. In the most popular analysis by Srivastava et al. [6], effective degrees of freedom in the hadron gas is increased. This reduces the life time of the mixed phase thereby reducing the photon contribution in low P_T region. In addition, tougher initial conditions $\tau_i = 0.2$ fm and $T_i = 335$ MeV, are used to enhance the photon contribution in high P_T region. In the work of Alam et al. [24], the flatter distribution is achieved by considering an initial radial velocity and in medium modification of hadron masses. In the work of Gallmeister [20], prompt photon contribution and transverse flow effect have been taken into account. Huovinen and Russkanen [25] have introduced a strong flow at later stages to explain the data. All these work [6,24,20,25] point to a short lifetime of mixed phase at SPS.

In conclusions, we have presented the results of investigations on different scenarios of a first order phase transition and analyzed SPS photon spectrum. The Supercooling which is an essential feature of first order phase transition has been included in the work. We find that the effect of supercooling is to marginally increase the photons in the low P_T region. A sudden hadronization scenario is ruled out at SPS. The so called fragmentation followed by freeze out seems to be the most appropriate scenario at SPS. This scenario supports a shorter life time of mixed phase at SPS which is also indicated by the previous analyses. The transverse expansion and finite baryon density have been neglected in the present work. The effect of finite baryon density is to reduce photons in high P_T region and increase in low P_T region [see discussions in [4]] which is opposite to the effect of transverse expansion. Thus, these two effects tend to cancel each other at SPS energy and are not expected to induce any qualitative change on the present work.

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