



The Reaction Models In Heavy Ion Collisions

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Abstract: For the description of the complicated dynamical system in quark gluon plasma state in relativistic heavy ion collisions our primary goal is to draw conclusions on the global equilibrium features of this confined state to find the largest colliding systems with longest collision times. The smaller colliding systems provide quite reliable results for some basic quantities, but when the final particle multiplicity is very large (of the order of several thousand), at some stage during the reaction local thermal and mechanical equilibrium are established for local volume of the size of $\approx 10 - 100 fm^3$. Such systems are beyond our possibilities. So in these problems the results are estimated by the comparison of experimental results with theoretical models, we have a number of possible reaction models. These reaction models are divided into two main categories: one category is of different fluid dynamical models and the other group is of microscopic String models.

Keywords: Heavy Ion collisions, Quark gluon plasma, Particle multiplicity, Fluid dynamical Model, String models.

I. Introduction

The field of relativistic heavy ion collision is interesting as well as difficult and they are on the borderline of applicability of different theoretical approaches. Basically two problems are there: The phenomena are smaller than macroscopic size but have short reaction time as compared to microscopic equilibrium. So the search is aimed towards drawing conclusions on the global equilibrium features of the hot and dense matter, consequently to the largest colliding systems which provide the longest collision time. It is not easy to describe such a complicated dynamical system in QCD, both due to the computational scope of the problem and due to the lack of principal microscopic information that would be necessary to solve the problem. The estimates from the comparison of experimental and theoretical results leave a wide range of reaction models. Reaction Models belong to two main groups: Some models are the fluid dynamical and continuum models which assume the existence of local equilibrium at some stage of the reaction (Not necessarily at the initial stage.). The second group of models assume the microscopic dynamics of the system like the constituents of the matter, their interactions, transitions, internal dynamics etc. not the local equilibrium. So the transport behavior of these systems is studied like by Monte-Carlo Simulations.

(A) Fluid dynamical models:

The simplest models come in this category like the Bjorken model (one dimensional scaling fluid dynamics), and the Landau model. The two models have different initial conditions corresponding to a situation after the initial impact, when the matter is already compressed and heated up and assume the complete stopping of baryons stemming from the projectile and target. The Landau model is most appropriate to apply in the energy range of 10-100 A.GeV. and the available energy is in the form of internal energy of the strongly Lorentz contracted disk of matter in the c.m. system and have no kinetic energy in the initial state, whereas Bjorken model is based on the assumption of linear scaling expansion in the beam direction in initial state. If we increase the energy further to $E_{c.m.} = 100$ A.GeV or above the expectation is that the Lorentz contracted nuclei will become transparent to each other, in a way that their valence quarks will almost maintain their original rapidities. At their interpenetration, however, these quanta may exchange some color charge which leads to the creation of a chromo-electric field similar to the electric field between two condensers.

Under certain conditions the time development in Landau model may reach to a situation, close to the initial state of Bjorken model. So in this case the subsequent developments and final state are similar in both models. Of course in general case the final states (break up states) of two models are not necessarily same. The resemblance of rapidity distribution observed at CERN-SPS and BNL-AGS experiments with Landau model is more acceptable and concludes that the stopping is large at these energies. But one cannot draw accurate

quantitative conclusions from it for the initial energy or baryon density, both due to the lack of knowledge of EOS and the similarity of final state of the two models. So at the present energies the use of Bjorken formula for the initial energy density is as an order of magnitude estimate. The transverse momentum spectra of several species of particles simultaneously by assuming a collective fluid dynamics expansion are described by simple model calculations more successfully [4,5,6,7]

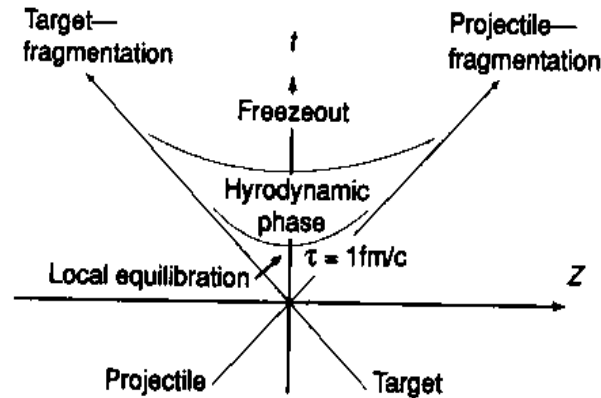


Figure 1: The space-time evolution of the mid-rapidity region in the Bjorken-model. The solution is uniform along contours of constant proper time. This ensures that the solution is invariant under Lorentz transformations in the beam direction.

(B) Detailed Numerical Models:

The Ultra-Relativistic heavy ion reactions can also be described by three dimensional detailed fluid dynamical models [8]. Apart from the numerical computational problems the difficulty is of selection of both the proper initial state and the equation of state of the problem. The three dimensional approach allows the most accurate determination of the stiffness of the nuclear matter, by the study of the phenomena of collective transverse flow. Let a Pb+Pb collision is considered at 160 A.GeV. With an EOS includes a strong first order phase transition to QGP [8]. If the initial state is chosen at the moment of impact of the Lorentz contracted nuclei and continue the fluid dynamics calculations from this moment. On assuming intermediate local equilibrium, we obtain a high temperature ($T > 400 \text{ MeV}$.) and density $0.5 \text{ fm}/c$, after the impact in a narrow region. By about $1.5 \text{ fm}/c$ the most of the central region is in QGP phase ($T > T_{cr}$), and is over the maximum compression even the temperature starts to decrease (Fig. 2).

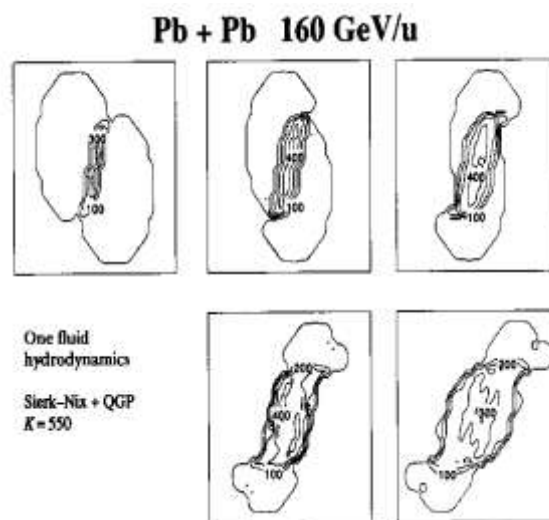


Figure 2: Contour lines of the temperature distribution, T [MeV], in the reaction plane of a Pb+Pb reaction of impact parameter $b=4 \text{ fm}$, at 160 A.GeV beam energy at c.m. times 0.34, 0.68, 1.03, 1.37, and 1.72 fm/c. The figures are distorted for better view; the size of the frame in the beam direction is 5 fm, while in the transverse direction is 20 fm. [8].

By this time the other models which do not assume the initial thermalization reach to a rather similar configuration, energy density distribution and these matches with the conclusion of similarity of final dynamics in Bjorken and Landau models. The two main features of final stage are observed here: (i) The density $1 \text{ fm}/c$

after impact and (ii) the freeze-out and final hadronization happens between 5-50fm/c after the initial impact. The transverse flow develops earlier (stronger by a factor of two), and assumes equilibrium earlier in fluid dynamical models than that of the string models [58]. So the simple model dynamical studies are performed mostly, because the dynamics of hadronization and freeze out are more problematic. [1, 2]

(C) *Microscopic String Models:*

To describe the heavy ion mechanism a set of models has been developed based on microscopic Monte-Carlo simulations of reactions. These are actually the extrapolations of lower energy Monte-Carlo cascade and Molecular dynamics models. The low energy models assume point like/compact particles (nucleons, pions deltas etc.) as constituents, moving in a force field of sum of interactions forces of all other constituents one by one.

(D) *Hadron-Hadron Reaction:*

From the studies at high energy (around 100A.GeV. or more), it is seen that the low energy picture is not appropriate, rather far from being binary and large number of reaction products(which follow a clear systematic in phase space) are created. The transverse momentum distribution of secondaries is relatively limited ($\approx 300\text{MeV}/c$), while the beam directed distribution is widely spread between projectile and target (nearly flat distribution in rapidity.) This led to the introduction of composite intermediate object, called string or flux tubes with an internal structure and space time development.

(E) *Strings:*

From the quark-parton picture of hadrons (hadrons are composed of valance quarks plus some sea-quark pairs). These composite objects are considered as strings or flux tubes, between two (group of) quarks and the confined chromo-electric field between them. By the pair creation from the strong fields a large number of secondary hadrons are formed. So the microscopic Monte Carlo models have strings added to the compact hadrons at these energies, and successfully describe the phenomenology of all hadron-hadron collisions.

(F) *Heavy Ion Reactions:*

When the same models were used to describe the heavy ion reactions, where the density of constituents was so large, several problems occurred. So the interaction of strings or the modifying effect of the dense surrounding cannot be neglected. The models which ignored secondary scattering and secondary strings formation, failed to describe the proton-rapidity distributions. Part of these string models which allowed the interactions of secondary hadrons and the string formation by secondary hadrons, successfully explained the experimental data on rapidity and P_t distribution of protons, K-mesons etc. By the comparison of these string models with experimental results, two facts are observed that (i) The string-string interactions and string fusion are necessary for the formation of more massive secondaries like strange antibaryons, because the single string formed by two or three valance quarks only did not carry the sufficient energy and (ii) To describe high P_t phenomena, minijets, gluon jets (specially at ultra relativistic energy) the hard partons should be included.

(G) *Monte-Carlo Model Families:*

(i) *Naïve String Models:*

These are early string models and just the naive extrapolation of hadron-hadron string models. These are still widely used to simulate the experimental data for the purpose of detector designing. The model based on Lund Model [12] is most commonly used, named FRITIOF model [11] (based on the Lund model).

(ii) *String Models with Rescattering:*

These models are more near to real picture in collisions and based on the concept of string formation in all hadron-hadron collisions, irrespective of the fact that the hadron is originated from the target or projectile nucleus or created during collision. The models belong to this category are RQMD versions without string fusion [13, 14, 15, 16,], VENUS versions without string fusion [17, 18, 19], QGSM [20, 21, 3], ACR [22] etc. The important feature of these models is that they strictly follow the hadron phenomenology with no additional assumptions, and able to produce closely identical results i.e. the best negative models without assuming collective effects (no QGP, no mass reduction of hadrons due to the environment etc.). But these models became self-contradictory in massive heavy ion collisions like Au+Au, or Pb+Pb at energies 200A.GeV. or higher where the string density becomes very high [21] and they have to overlap, so the assumption of independent non-interacting strings is broken. These models describe correctly the stopping power and most observables but fail to reproduce the heavy secondary production like strange anti-baryons.

(iii) *Models with String fusion:*

These string models are finding the remedies of the problems in the previous models. The remedy is the formation of some heavier composite objects having more valance quarks by the fusion of strings. The models in this group are RQMD versions with string fusion, VENUS versions with double strings [23], string fusion model (SFM), [24] etc. Although these models are now able to describe the experiments the previous family failed to reproduce, new ad hoc parameters are introduced, like string string cross section, modification of string tension in fused strings. These models are successful up to an extent but still these are not based on hadron phenomenology and not able to provide a much more basic understanding of the problem.

(iv) *Parton Cascade Model:*

For higher energies (Fermi-lab, RHIC, LHC) the correct description of hard parton-parton collisions is very difficult. These models may abandon the idea of strings altogether and the parton cascade is happening in the perturbative vacuum [25]. The transition from the physical vacuum to the perturbative one, as well as, the final hadronization and return to the physical vacuum is a sensitive part of these models. In any case these models are allowing dynamical processes leading to the equilibration of the parton matter and in some models the equilibration and thermalization are explicitly tested and achieved. Some models keep the string idea to a certain extent and the parton cascade takes place in limited clusters. But the detailed experimental testing of these models is still in progress. The sequence of the above mentioned models provides a gradual approach to QGP. The objects (strings) which are considered in the models are becoming larger corresponding to bigger and bigger density of quark matter in non-equilibrium. The approach to equilibrium is discussed only in some of the models of the last, family. It is academic to ask if these models are supporting or are against the assumption of a Quark Gluon Plasma based on the presently available results of these models. Each of the above string models should have a stationary equilibrium solution also, and consequently an Equation of State. In principle, however, it is possible to determine the underlying EOS for any of these Monte-Carlo models, just the model prescriptions should be applied to a large fixed container of matter, and the equilibrium properties studied. Unfortunately this is not done in any of the models till now. Nevertheless, it cannot be excluded that these string models have a first order phase transition in their EOS, since the strings have a substantial amount of energy, which is latent, i.e. it is an internal energy and it is subtracted from the kinetic energy of the constituents leading to the pressure of the material. These questions are expected to answer in the next few years of research.

II. Summary & Conclusions

The reaction models which are used to study the heavy ion collisions are very much useful to understand the features of complicated quark gluon plasma state. Some of them are simple fluid dynamical models, which assume complete stopping of baryons stemming from the projectile and the target nuclei, which is true for the Landau model and the spherical model. The Bjorken model is also a fluid model and it also assumes complete stopping, however, the initial condition is such that the fluid dynamical regime was preceded by a non-equilibrium stage, where the projectile and target baryons penetrated each other. Thus anyone fluid model with a well chosen initial condition can describe the final equilibrated stages of a collision. String models are applicable at CERN-SPS and BNL-AGS energies. The soft quark-quark collisions are described by "String" formation and subsequent hadronization. But it is quite uncertain how these strings attach with quark and gluons, also what happens when they overlap in space. So the models which assume the independent string are questionable also we certainly have rescattering before secondaries come out of the system. So for that we have different string models like string models with rescattering, string models with string fusion and the parton cascade model with different conditions which provide a very good explanation but not more basic understanding of the problem. So the field is still open and far to go in search of QGP state completely.

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