



Simulation Modeling in Heavy Ion Collisions

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Abstract: In current epoch, it is mandatory to develop a system with prior project management consisting high-quality estimation, prediction and prototype creation of the entire system and its components, stating their work flow and all the major mechanisms. Simulation modeling is a procedure which helps in development and analysis of a digital prototype of a physical model to predict its performance in the real scenario. We can use the simulation study to describe quark gluon plasma (QGP) state of matter, which can be created in the laboratory by colliding nuclei at RHIC, LHC energies. This phase undergoes a transition to hadrons, which carry information about the state of the QGP. Measuring these hadrons and their features is the only way to study the properties of the high density state. In this work we will study how the properties of QGP can be extracted by analyzing the signatures like J/ψ production, Dilepton production, Strangeness production, Collective flow etc. The simulation techniques are implemented with the help of event generators like HIJING (Heavy Ion Jet Interaction Generator), AMPT (A Multi Phase Transport Model) etc. for the search of global variables of QGP state.

Keywords: Heavy Ion collisions, Quark Gluon Plasma, Simulation Modeling, Even generator, Global variables.

I. Introduction

The quantum chromo dynamics calculations on lattice predict that if the heavy nuclei are collided at extremely high energy densities and temperature the matter would undergo a phase transition and the temperatures are so high that protons and neutrons split into their constituents, the quarks and gluons. This state of matter is defined as the quark gluon plasma (QGP). The electron collision experiments on proton indicate the internal structure of nucleons as they are built of quarks and gluons. This quantization is described by quantum chromo- dynamics (QCD) field theory, and this tells that quarks and gluons cannot be found freely as they are confined by strong interaction which binds them to each other. This tie is defined by a quantum number called color. At high energy density the quark gluon plasma state can be expected in laboratories at projectile energies of the order of 10-100A.GeV. This is the only possibility to produce unbound quarks and gluons, in a small volume and in a large number in the reaction zone. The nature of the phase transition the temperature and the energy density depend upon the quark flavors. This new state of the matter existed in the universe after few micro seconds of the big bang [Fig. 1].

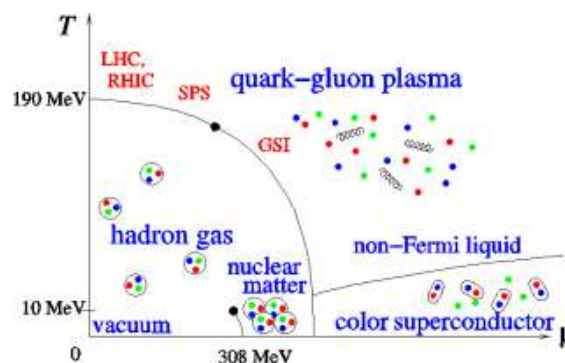


Figure 1: The quark gluon plasma state and the hadronization.

As the universe is cooled down further in subsequent phases the quarks and gluons combined to form hadrons resulting in the baryonic matter that we observe today. This state of matter can be created in laboratory by colliding nuclei at RHIC and LHC energies and the long range properties of nuclear matter for comparatively small systems can be studied. By changing the bombarding energy as well as the projectile & target nuclei combinations, the systems of different energies and baryon density can be created in laboratories.

The major curiosity associated with the transition from the QGP to baryonic matter is the experiments which are going on in this field to study the observable phenomena associated with the dynamics of this interface. These experimental programs involve the collision of relativistic heavy ions that produce (relatively) small drops of QGP. Large particle detectors are able to analyze and study systems the products of these collisions, which provide description and information about the transition to the baryonic phase and the QGP itself.

From the last few decades the high energy physics has changed revolutionary as we have many accelerators like Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory (BNL) and Super Proton Synchrotron (SPS) at CERN (European Center For Nuclear Research) etc. which can accelerate heavy ions at large energies. The measurement of these hadrons and their features is a very good tool to analyze the properties of this highly dynamical and dense state. This quark to hadron transition is called chemical freeze out. The measurement of the various particle ratios (which is fixed in this stage) provides the information about the conditions at this transition point, within the framework of some statistical models. Further evolution reaches to the kinetic freeze out stage, beyond which particle stream freely to the detectors.

Bulk Properties: Soft Physics

The major bulk of the particles produced in heavy ion collisions are with transverse angular momentum $P_t < 1.5\text{GeV}/c$. The determination of identity of these particles and their kinematic variables enable us to determine most of the global variables, of heavy ion collisions (to reflect the properties of the matter produced in heavy ion reactions.)

Energy density:

The measurements by experiments reveal that the transverse energy per particle produced is independent of colliding energy, so the measured particle energy directly determines the energy density for a given collision.

Chemical Freeze-Out:

Since the energy density is large enough to support to the formation of extremely dense matter i.e. the quark gluon plasma, so now it's imperative to estimate the temperature at which the matter hadronizes. That point in the collision is called the chemical freeze-out. The measured ratio of yields of hadrons put limits on the values of system temperature and baryon chemical potential at chemical freeze-out. For example in Cu-Cu collision the chemical freeze-out is estimated at $\approx 155\text{MeV}$.

Kinetic Freeze-Out:

At chemical freeze out the particle produced interact to each other and the space time evolution of these particles can be modeled using hydrodynamics because in this state the matter behaves like a fluid. This hydro dynamical modeling is able to predict the transverse momentum distribution of particles called the spectra. So the hadron spectra reflect the integrated effect of expansion from the beginning of the collision and to the later conditions. This indicated more rapid expansion of collision after chemical freeze-out, called the kinetic freeze-out.

Collective Flow:

The meaning of collective flow in heavy ion reactions is the emission of same type of particles or emission of many ejectiles with a common velocity field or into a common direction. There are several collective phenomena in heavy ion collisions.

1. The longitudinal flow, which describes the collective motion of particles along the original beam direction.
2. The radial flow means the flow of particles with common velocity field with the spherical symmetry.
3. The transverse flow represents the flow when the velocity field is independent of azimuthal angle.
4. The impact parameter vector orientation defines a specific azimuthal direction in nucleus-nucleus collision and a large emission is observed experimentally in this direction called the "elliptic flow".

Azimuthal anisotropy (the elliptic flow):

One of the major experimental evidences for the existence of thermalized system is the observation of large anisotropic flow of hadrons.

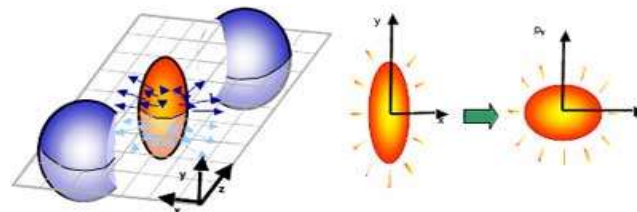


Figure 2: Left: Schematic of the collision zone between two incoming nuclei and x-z is the reaction plane. Right: Initial-state anisotropy in the collision zone converting into final-state elliptic flow, measured as anisotropy in particle momentum.

The emission of particles correlated with the reaction plane is termed as anisotropic flow. Azimuthal asymmetry in the overlap region increases with increasing impact parameter. The yield of various hadrons with respect to

the reaction plane can be characterized by Fourier expansion, where the different coefficients measure different anisotropies present in the system. The first coefficient is known as the directed flow (v_1) and the second coefficient is the elliptic flow (v_2).

The elliptic flow measures the effect of unequal pressure gradients, along and perpendicular to the reaction plane, and the extent of thermalization of the system. Its value increases with particle density and the large values observed experimentally, indicates that the thermalized system behaves like ideal fluid. So the hydro dynamical models are adapted for the explanation of radial and elliptic flow.

The bulk properties discussed above indicate that hadrons are emitted from a thermalized and strong and collectively expanding source, after reaching to chemical equilibrium.

Hard probes:

There are some other signals and probes for gaining the information about the state of matter in heavy ion collisions like:

(i) Dileptons:

This is an electromagnetic probe i.e. the photons and lepton pairs (dileptons) do not participate in the strong interaction and can therefore mediate important information on the electromagnetic current correlated in the interior of the hot and dense matter. These are the important tools to study the heavy ion collisions at ultra-relativistic energies. So they carry the signature of primordial state of the matter produced, and their spectra are nearly unaffected by the final state hadronic interactions.

(ii) J/ψ Suppression:

In the search for quark-gluon plasma (QGP), J/ψ suppression is proposed as one of the important signals [1] of the deconfinement in high-energy heavy-ion collisions when the matter is in the deconfined state of quarks and gluons the colour charges of quarks are screened in colour plasma. This is similar to what is seen in electromagnetic plasma. The screening of colour charges is characterized by Debye screening. In normal circumstances the linear confining potential in vacuum binds two heavy quarks to form a quarkonium but in the presence of Debye screening the strength between quarks is effectively decreased, and does not allow the formation of bound state. Thus causes the suppression of J/ψ production.

(iii) High p_T hadron yields & Jet Quenching:

When the scaling behaviour is investigated in different p_T regions, it is observed that the yield of high p_T hadrons is suppressed in central collisions. This suppression suggests the presence of final state interactions of hard scattered partons. Due to the large bombarding energies at RHIC, high transverse momentum (p_T) particles become statistically abundant in heavy-ion collisions. High p_T particles come predominantly from jets emerging from initial hard-scatterings between partons. They require sufficient time to go away from the collision zone, and mean while a dense medium is formed. The partons and fragmented hadrons are expected to lose energy via interactions with the medium (mostly by gluon radiation), and the high p_T particles are quenched. This is called the jet quenching phenomena - suppression of yield and angular correlation strength at high p_T [5]. The larger the medium gluon density, stronger the interaction and the larger the suppression magnitude. Thus, high p_T particles and jet quenching provide a powerful, direct tool to measure the density of the medium created in ultra-relativistic heavy-ion collisions. So by studying these signatures at high energies we are in search of the features of this deconfined state of matter i.e. the quark gluon plasma. There are some theoretical models which are used to understand the situation theoretically, and they provide a very good agreement with the experimental results.

The theoretical models:

In heavy ion collisions when the system reaches to the hydrodynamic regime, this state can be well described by the theoretical simplification and provides a quasi-microscopic description, with the help of hydro dynamical models. This was actually the first approach to predict the behaviour of the system and their collective behaviour [2, 3]. But soon it was observed that the assumption of instantaneous local equilibrium in ideal fluid hydro dynamics is not fulfilled in heavy ion collisions, when compared with actual data, even the viscosity and freeze out concepts were also introduced [6]. To overcome these complications, the models based on superposition of individual N-N collisions were developed. In the starting the simple concept of overlaying independent N-N collisions were considered [7, 8], because the collective side flow effects were missed in the early cascade models. Further they were refined by introducing collective mean fields i.e. the particles propagate in their common nuclear mean field and experience hard two body collisions, when their distance in space & time is small enough. Further they were divided into two different program classes: (a) RBUU, for relativistic Boltzmann –Uhling Uhlenbeck, the approach which was limited to single particle distributions because it propagates test particles in the common mean field of several parallel collisions [9, 10].

(b) RQMD, for relativistic quantum molecular approach in which the individual collisions and the fluctuations are described by the treatment of particles as classical wave packets [4, 11, 12] The transport models provide the study of influence of different EOS (equation of state), different momentum dependences of the interactions and in medium cross-sections on all observables. With these inputs the results from different models are generally in agreement with the real data. But still the proper strategy to describe the Ultra-relativistic energy range collisions is not yet established.

The Simulation Techniques:

For a long time the simulation techniques in heavy ion collisions are rather more phenomenological in nature. As experiments became more sophisticated and inclusive, the need for the advanced simulation models appeared. The transport models are one of those microscopic models which are able to dynamically simulate the collisions without any assumption to thermal equilibrium. Like RBUU is a semi-classical simulation technique (theoretical model as mentioned above). The semiclassical transport code can work reliably at energies beyond 100 MeV. Per nucleon. Transport models have successfully described many aspects of intermediate energy heavy ion collisions.

Event Generators:

Event generators are aimed to describe the heavy ion collisions deeply by making use of physics known from p-p scattering. So the dynamics of A-A collision can be considered as particles produced in initial binary collisions and subsequent rescattering produces the secondaries. In order to include these rescattering, particles are used as explicit degree of freedom and individual particle trajectories and reactions are followed through the evolution. This can be done when the particles are treated as localized wave-packets, also the reaction cross-sections are implemented by purely geometrical considerations. Observables are then calculated by Monte-Carlo simulation of a large sample. We have a variety of event generators which are dependent on degrees of freedom employed, the way of hadronization and the use of additional physics which is not considered in p-p collision. Most prominently used are, HIJING [20] tracking hard partonic evolution and hadronization. RQMD [18], & UrQMD [19] tracking hadronic degrees of freedom, and LUCIFER [21] etc. Once the transition to hadronic degrees of freedom from either strings or partons has been made, measured hadron-hadron cross sections enter the simulation and the model dependencies greatly reduced. To understand experimental results of these global variables, we required simulations study for the same. For Simulations: We will generate events using HIJING and AMPT event generator for different energies. We will produce the results for global variables using these data. We will compare these results with experimental data. Provided by various experiments and also explain these results by putting a suitable theoretical explanation.

HIJING (Heavy Ion Jet Interaction Generator.), the Monte Carlo Model :

It is expected that hard and semi-hard parton scattering with transverse momentum of a few GeV, dominate high energy heavy ion collisions. The HIJING model was developed by M. Gyulassy and X.N. Wang with special emphasis on the role of minijets in pp, pA, AA reactions at collider energies. The systematic comparison of results with HIJING, with a very wide range of data demonstrates that a quantitative understanding of the interplay between soft string dynamics and hard QCD interaction has been achieved. In particular, HIJING reproduces many inclusive spectra two particle correlations, and can explain the observed flavor and multiplicity dependence of the average transverse momentum. It is basically designed to simulate multiple minijets and particle production in pp, pA, & AA collision. HIJING is written in FORTRAN 77, consisting of subroutines for physics simulation and common blocks for parameters and event records.

The main features added to HIJING are:

1. The modeling of soft beam jets using the Lund FRITIOF and the dual parton model DPM [13]. In addition multiple low p_T exchanges among the end point constituents are included to model initial state interactions.
2. Multiple minijets production with initial and final state production is included, along the lines of the PYTHIA model.
3. The impact parameter dependence of the number of inelastic processes is calculated by exact diffuse nuclear geometry.
4. A model for jet quenching and an impact parameter dependent parton structure function are introduced.

AMPT (A Multi Phase Transport Model.)

AMPT is a Monte Carlo transport model for hadron-hadron, hadron-nucleus and nucleus-nucleus heavy ion collisions at relativistic energies. This model has four main parts: the initial conditions, partonic interactions, the conversion from partonic to hadronic matter and hadronic interactions. It uses the Heavy Ion Jet Interaction Generator (HIJING) for generating the initial conditions which include the spatial and momentum distributions of minijet partons and soft string excitations, the Zhang's Parton Cascade (ZPC) [14] (includes only two-body scatterings with cross sections obtained from the pQCD with screening masses) for modeling partonic scatterings, the Lund string fragmentation model or a quark coalescence model for hadronization, and A Relativistic Transport (ART) model for treating hadronic scatterings, are improved and combined to give a coherent description of the dynamics of relativistic heavy ion collisions [15, 16, 17, 18]. At present, this model includes only gluon-gluon scatterings.

II. Summary & Conclusions

The information collected till today about the field of heavy ion collisions is still far away from the complete exploration. The important developments are expected in this direction like up gradation of RHIC detectors which can provide more precise results about anisotropic flow, strangeness production, J/ψ production, strangeness and other important features. Moreover the important thing is to search the critical point of QGP state. The RHIC beam energy scan would cover the region from top AGS energies, over CERN & SPS energies and higher.

The main difficulty of event generators is found in the initial multi-particle production. Because of the contribution of both soft and hard processes, the choice of the correct degrees of freedom is therefore not obvious. Usually, soft particle production is calculated in the framework of the Dual Parton Model or the Lund string model it describe the particle production as the of color strings stretching breaks between the scattered partners. For the hard particle production, partonic degrees of freedom have to be employed along with the fragmentation functions known from e.g. deep inelastic scattering experiments. If there is any QGP phase, its properties are encoded in nontrivial physics of particle production within event generator type models. Suggested concepts involve interactions or fusion among color strings ('color ropes', implemented in RQMD and UrQMD), percolation of strings and modifications of the string tension (HIJING). In general, the implementation of these additional mechanisms allows no straightforward connection to equilibrium properties of the QGP extracted from the lattice, which makes it difficult to make use of this information.

These days we have detailed simulation studies of such collisions with the methods developed for desired geometry of the collisions. The results from different simulation models are providing good agreement with the experimental results at low energies and relativistic energies as well as at high energies.

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