Scientific Report 2014

Obtaining of new experimental results on the chemical freeze-out in Au-Au, Cu-Cu and p-p at the available energies at RHIC-BNL

The problem of the freeze-out, both chemical and kinetic, is an interesting objective of the major scientific programs in Relativistic and Ultrarelativistic Nuclear Physics, from all international laboratories in the field (CERN, BNL, GSI-FAIR, JINR). This objective is strongly connected to the exploration of the phase diagram of the nuclear matter, in connection with the investigation of the deconfinement and chiral symmetry restoration

For achievement of the scientific objectives, for this stage, is related to the performing of simulations with different codes (AMPT, UrQMD). These were focused on the nucleus-nucleus collisions that will be performed at the Experiment CBM from FAIR-GSI Darmstadt. In the present stage of the preparation of the experiment interesting problems are related to the selection of the positions of the different detectors. In addition, the necessity of the comparisons of the simulation codes predictions with the existing experimental results, for an increased confidence in selected codes, is, also, important. The experimental results obtained in BRAHMS Collaboration from RHIC-BNL have been used.

The phase transition from a deconfined system of quarks and gluons to a system formed by hadrons can be reflected by the values of some interesting physical quantities, the associated distributions, as well as by the fluctuations, especially those of higher orders and cumulants. It is expected as the large fluctuations in the baryons number and in associated electrical charges offer indications on such transitions. The dependencies of different physical quantities and associated fluctuations on the interaction energies of the heavy ions could indicate the existence of phase transitions, too. In these conditions it is important that the experimental set-up be able to offer confidence information on the collision centrality and yields for different particle types, as well as on the kinematical characteristics. In these conditions, adequate information on the dynamics of the nucleus-nucleus collisions at the available energies can be obtained. Such information, associated with those on the phase transition in nuclear matter is expected from the experiments from FAIR-GSI, too.

The problem of selection of the positions of detectors in the CBM Experiment is an interesting problem of the collaboration and the group, too [1-3]. This aspect is a continuation of the preoccupations those permitted investigations using the experimental data obtained in the Experiment BRAHMS form RHIC-BNL.

The previous preoccupations for describing the dynamics of the relativistic nuclear collisions using methods base by chaos concept have been continued. The particle production mechanisms can be reflected by the rapidity distribution. This quantity reflects the conversion of the initial longitudinal movements of the nuclear systems in the transverse movements of the generated particles in the interaction process of the colliding nuclear systems. In this stage, a multidimensional Lyapunov exponent has been introduced, namely:

$$L = \lim \frac{1}{t} \ln \frac{d(t)}{d(0)} = \lim L(t), \quad t \to \infty , \qquad (1)$$

where d(t) represents the distance in space phase between the two nuclear systems and is defined as follows:

$$d = \sqrt{\sum_{i=1}^{n} \left[\left(\vec{r}_{i1} - \vec{r}_{i2} \right)^2 + \left(\vec{p}_{i1} - \vec{p}_{i2} \right)^2 \right]} . \quad (2)$$

Here, r_{i1}, p_{i1}, represent position and momentum, respectively, for the i-th particle from the first nuclear system, and r_{i2}, p_{i2}, are the analog coordinates for the second nuclear system.

Because the structure of the system of many bodies can modify during the temporal evolution, for application of the previous relationship must be done in specific conditions. Thus, the previous „global" way supposing the calculation of the distance using the relation:

$$d = \sqrt{\left(\sum_{i=1}^{n_1} \vec{r}_{i1} - \sum_{i=1}^{n_2} \vec{r}_{i2}\right)^2 + \left(\sum_{i=1}^{n_1} \vec{p}_{i1} - \sum_{i=1}^{n_2} \vec{p}_{i2}\right)^2} \qquad (3)$$

was changed with a new way.

This is an intuitive method/way. For a constituent composed by many bodies the following set is considered:

$$M_i = \left\{ x_i(t), y_i(t) \middle| \frac{dp_{xi}}{dt}(t) = 0 \vee \frac{dp_{yi}}{dt}(t) = 0 \right\}. \qquad (4)$$

With this set a „clusterization map" is defined: $M = \bigcup_{i=1}^{n} M_i$ *.This new method permits a „bi-dimensional projection" of all clusters created in the interior of the nuclear system formed by collision. The associated calculation program searches for all points where the signs of the associated derivatives are changed. For describing the fragments formation or the baryonic/mesonic resonances formation some free particles can be excluded form system. In addition, to the conditionings related to the conservation of the total energy, a test giving a measure o the accuracy of the simulation has been introduced. Thus, for ordinary simulations, inverse processes can be considered. In these conditions, the initial state of the considered system can be compared with the final state for the inverse process, using the space phase distance defined previously. In this manner the confidence level in the predictions with the new code increases. The introduction of a Lyapunov structural function taking into account the temporal evolution is necessary.*

The method has been applied to the predicted data obtained with different simulation codes for nucleus-nucleus collisions at the energies available at FAIR-GSI. It was applied for describing experimental results obtained in symmetric nucleus-nucleus collisions at similar energies. Thus, the experimental results obtained in C-C collisions at 4,5 A GeV/c (SKM Experiment, Synchrophasotron, JINR Dubna) [4]. In the performing of the simulations, the following hypothesis has been introduced: the colliding nuclei are represented by two distinct sets of nucleons placed, initially, in a cubic box, with edges placed at distances equal with the nucleus radius, $r = r_0 A^{1/3}$*. The target is, initially, in repos, and the constituents momenta of the projectile system can be specified as parameters. The Lorentz contraction was neglected. A Yukawa potential with finite depth has been used. To this potential two additional terms has been added, namely: a Coulomb term and a repulsive term, specific to the strong interaction, of short distance (*V_0 *=35 MeV, a=2 Fm, k=200). The simulated results, together with the experimental results are included in the Fig.1. The proposed model describes well the angular distribution, and, in consequence, the pseudorapidity distribution. There are some quantitative discrepancies in the descriptions of the energy and momentum distributions. Taking into account the definition relation of the rapidity, namely:* $y = \frac{1}{2}\ln\frac{E + p_L}{E - p_L}$*, the attenuation of the discrepancies in the rapidity distribution can be observed. Similar behaviours have been observed for other nucleus-nucleus collisions, at different energies. These observations permitted the introduction of new calculation hypotheses in the simulation code based on chaos quantities. These increased the concordance among the code predictions and experimental results [5,6].*

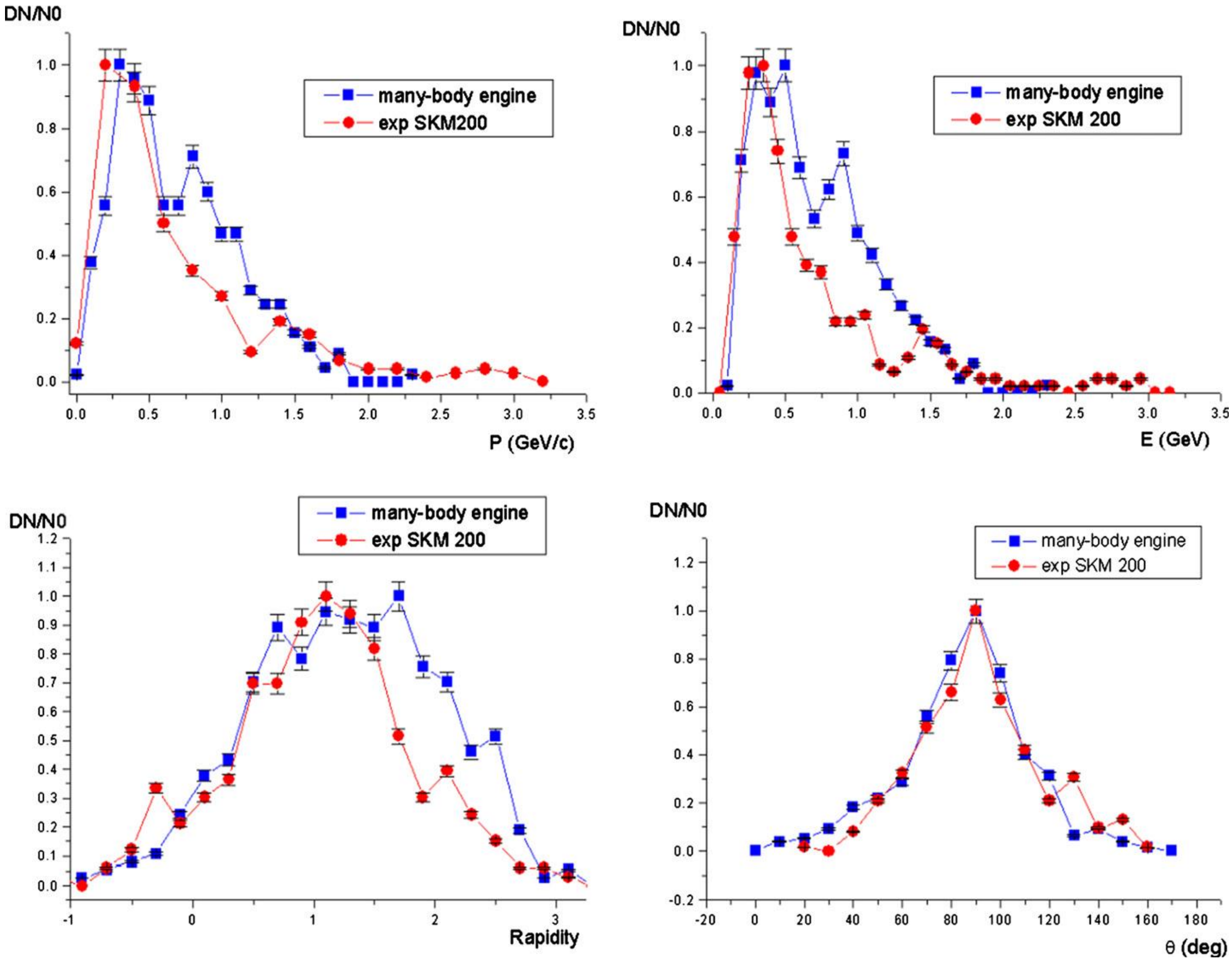

Fig.1. Comparisons among the experimental distributions and simulated distributions for a few interesting physical quantities (energy, momentum, rapidity and emission angles) for C-C collisions at 4,5 A GeV/c

Other interesting working direction was related to the performing of some simulations with different important codes, as well as of the comparisons with the experimental results, mainly with those obtained in the BRAHMS Experiment.

At the performing of the simulations a few aspects have been taken into account. First, the majority of the experimental results reflect the hydrodynamic behaviour of the hot and dense nuclear matter formed in the overlapping region of the colliding nuclei. Secondly, at the selection of the results the strong connection of the interesting physical quantities with the total energy available in the center of mass system (CMS), collision geometry, rapidity range and particle types have been taken into account. Therefore, to the experimental results, the group considered simulations for other collisions at different total energies in CMS. Creation of data basis and beginning of introduction of the analysis methods taking into account the structure of detectors and the nature of the signals of detectors have been considered, too. This fact is important taking into account that the dependence on the rapidity range is correlated to the number of participants and particle production mechanisms. There is a large variety of investigation methods. For example, a way supposes the explosion of the participant region, *extremely dense, and formation of blast waves. Thus, by the fit the transverse momentum spectra of the charged particles with the functions describing the evolution of the shock waves, taking into account the fact that the emission of each particle type is done with a specific probability, weighted for different time moments from the fireball evolution, in consequence at different temperatures and densities of the fireball, the parameters for the kinetic freeze-out have been obtained.*

*One of most used simulation codes for description of the dynamics of the relativistic nuclear collisions is those of ultra-relativistic quantum molecular dynamics, with acronym UrQMD (**U**ltra-**r**elativistic **Q**uantum **M**olecular **D**ynamics). This is a transport model and it permits simulations for nucleus-nucleus collisions dynamics at the available energies from those existing at SIS-18 (GSI Dramstadt), to those existing at (CERN Geneva). Using this simulation code a large variety of interesting physical phenomena can be studied, form nuclear multi-fragmentation and collective flow, to the particle production mechanisms and correlations in particle production. If the hard scattering processes are taken into account, in accord with the perturbative Quantum Chromodynamics, the code can include PYTHIA type routines. These were proposed by a group from the University of Lund (Sweden). The physical basis of the model for such routines are presented in the works [7,8]. The analysis of the hydrodynamic behavior of the nuclear matter was initiated in the paper [9]. From the beginning of the model and the associated simulation codes, the possibility of the connections among the hydrodynamic behavior of the hot and dense nuclear matter with the phase transitions in nuclear matter have been investigated. A special attentions was paid to the phase transition to the quark-gluon plasma [10,11].*

*Another simulation code used frequently in the description of the behavior of the high excited and dense nuclear matter is based on a multi-phase transport model for relativistic nuclear collisions [12,13]. The associated simulation code, with acronym AMPT (**A** **M**ulti-**P**hase **T**ransport model), used a combined model taking into account both partonic phase and hadronic phase. The code used the code HIJING (**H**eavy **I**on **J**et **I**nteraction **G**enerator) to generate the initial conditions, the simulation code ZPC (**Z**hang's **P**arton **C**ascade) for the modelation of the partonic scatterings. The AMPT simulation code includes, for hadronization processes description, components of the Lund model for the strings fragmentation, as well as the quark coalescence model. For treating the hadronic scatterings a relativistic transport model (ART – **A** **R**elativistic **T**ransport model) is included, too. A coherent description of the dynamics of the relativistic nuclear collisions is possible. A large variety of parameters can be estimated. The predictions of the simulation code and associated model are strongly dependent on the input parameters. The AMPT simulation code there is in two versions. There is a basic version – called AMPT – and a version using strings theory, taking into account the melting of the strings. The initial conditions are slightly different for the two versions of the code. The AMPT simulation code – in both versions – permits consideration of large specific aspects from the dynamics of the relativistic nuclear collisions, from the form of the rapidity distributions to the elliptic flow and production of the particles with heavy flavours (charm, bottom). Therefore, the AMPT simulation code is intensively used in the last period [14,15].*

In the present work, simulations with both codes, UrQMD and AMPT, have been done. The comparisons with the experimental results obtained in Au-Au collisions at the available energies at RHIC-BNL begun.

***In** Table I the simulated data obtained using UrQMD code for Au-Au collisions at the available energies at RHIC-BNL and at SIS-100 and SIS-300 from FAIR-GSI, respectively, have been included. In Fig.2 are presented the rapidity distributions of the positive pions for the 6 energies considered in Table I. The dependence on the beam energy can be observed. The transverse momentum distributions for positive kaons yield in Au-Au collisions at* $\sqrt{s_{NN}} = 62\,GeV$ *- for 4 collision centrality ranges – are presented in Gig.3. The distribution of the antiproton to proton ratio as a function of rapidity is shown in Fig.4, for a few interesting energies. The dependencies on energy and rapidity are extremely important. The* *indications related to the possibilities for identification of the optimal conditions for different phase transitions in highly excited and dense nuclear matter are important, too. The predictions of the simulation codes and the model calculations are in good agreement with the experimental results. Specific developments are in work, in present.*

Collision	*Energy*	*No. of events*
Au-Au	$\sqrt{s_{NN}} = 200\,GeV$	*10000*
Au-Au	$\sqrt{s_{NN}} = 62\,GeV$	*10000*
Au-Au	$p_{SL} = 25\ AGeV/c$	*42000*
Au-Au	$p_{SL} = 11\ AGeV/c$	*100000*
Au-Au	$p_{SL} = 5\ AGeV/c$	*100000*
Au-Au	$p_{SL} = 2\ AGeV/c$	*100000*

Table I Simulations with UrQMD code

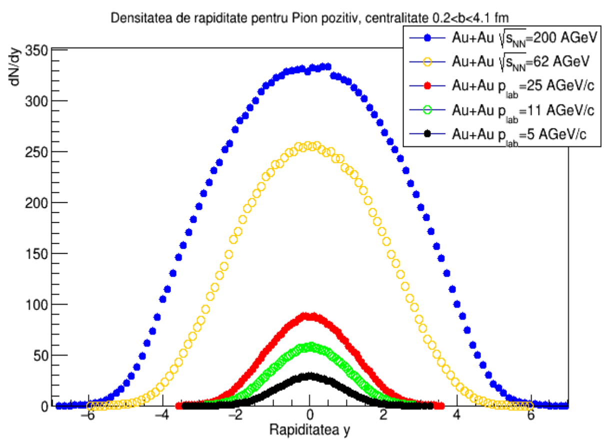

Fig.2. Rapidity distribution of the positive pions in Au-Au collisions at RHIC-BNL energies

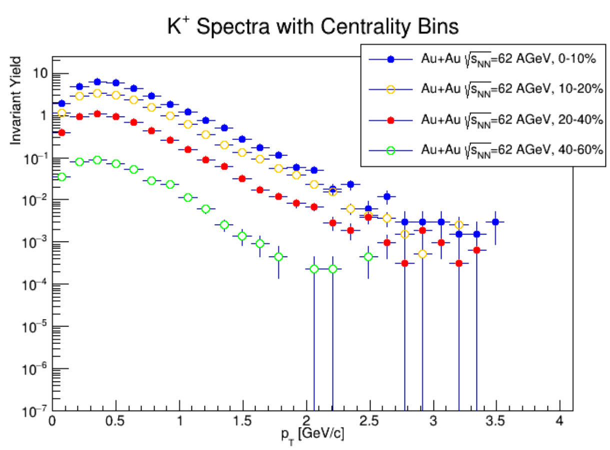

Fig.3. Transverse momentum distribution of the positive kaons in Au-Au collisions at $\sqrt{s_{NN}} = 62\,GeV$

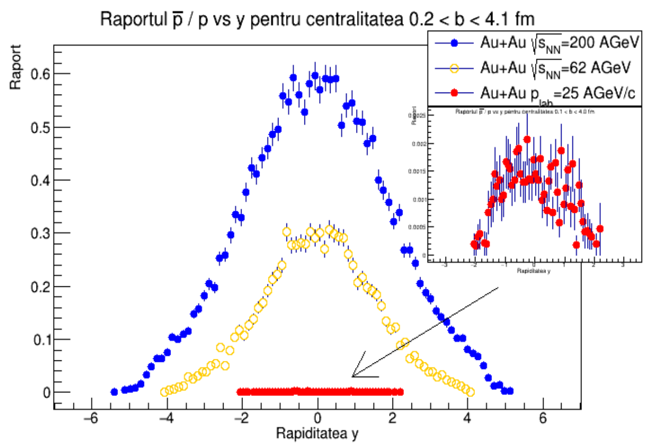

Fig.4. Antiproton to proton ratio, for different energies, as a function of rapidity

These results are completed by other activities performed by the research team of the project in the last period. The simulations done for Au-Au collisions at the energies that will be available at FAIR-GSI at the two accelerator systems, SIS-100, SIS-300, respectively, completed the needed information. The comparisons with the existing experimental results obtained in the frame of the BRAHMS Collaboration from RHIC-BNL have been done, too. All are in different stages, being published or presented at national and international conferences [16-21].

In conclusion, all results obtained up to now offer a good support for the accomplishment of all tasks proposed in project.

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