Formation of the intermediate baryon systems in hadron-nuclear and nuclear-nuclear interactions

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Abstract

The centrality experiments indicate regime change and saturation in the behavior of some characteristics of the secondary particles emitted in hadron-nuclear and nuclear-nuclear interactions at high energies. The phenomenon has a critical character. The simple models do not explain the effect. We suppose that the responsible mechanism to explain the phenomenon could be the formation and decay of the intermediate baryon systems. Such systems could be formed as a result of nucleon percolation in compressed baryonic matter. Formation of big percolation cluster may change the properties of the medium, e.g., it could lead to the changing its transparency. This could be used to get a signal of the intermediate baryonic system formation. We consider two signals to identify the formation of the intermediate baryon systems: the critical changing of transparency of the strongly interacting matter and the enhancement of light nuclei production with increase in centrality.

1 Centrality experiments

One of the important experimental methods to get information on the changes of states of nuclear matter by increasing its baryon density is the study of characteristics of hadron-nuclear and nuclear-nuclear interactions depending on the centrality of collisions at high energies. On the other hand the centrality of collisions cannot be defined directly in the experiment. In different experiments the values of centrality are defined as the number of identified protons, projectiles’ and targets’ fragments, slow particles, all particles, as the energy flow of the particles with emission angles $\theta = 0^0$ or with $\theta = 90^0$. Apparently, it is not simple to compare quantitatively the results on centrality-dependences obtained in literature while on the other hand the definition of centrality could significantly influence the final results. May be this is a reason, why we could not get a clear signal on new phases of strongly interacting matter, though a lot of interesting information has been given in those experiments. Let us consider some of the experiments.
1.1 Hadron - Nuclear Interactions

In Ref. [1] the results from BNL experiment E910 on pion production and stopping in proton-Be, Cu, and Au collisions as a function of centrality at a beam momentum of 18 GeV/c are presented. The centrality of the collisions is characterized using the measured number of ”grey” tracks, $N_{\text{grey}}$, and a derived quantity, the number of inelastic nucleon-nucleon scatterings suffered by the projectile during the collision. In Fig. 1 are plotted the values of average multiplicity for $\pi^-$-mesons ($<\pi^-\text{Multiplicity}>$) as a function of $N_{\text{grey}}$ and for the three different targets. We observe that $<\pi^-\text{Multiplicity}>$ increases approximately proportionally to $N_{\text{grey}}$ and for all three targets at small values of $N_{\text{grey}}$ or $\nu$ and saturates with increasing $N_{\text{grey}}$ and in the region of higher values of $N_{\text{grey}}$ and $\nu$. Solid line in figure shows the expectations for the $<\pi^-\text{Multiplicity}>$ ($\nu$) based on the wounded-nucleon (WN) model [1] and with dashed lines, does a much better job of describing p-Be yields than the WN model.

BNL E910 has measured $\Lambda$ production as a function of collision centrality for 17.5 GeV/c p-Au collisions [2]. Collision centrality is defined by $\nu$. The $\Lambda$ yield versus $\nu$ is plotted in Fig. 2. The open symbols are the integrated gamma function yields, and the errors shown represent 90% confidence limits including systematic effects from the extrapolations. The full symbols are the fiducial yields. These various curves represent different functional scalings. We see that the measured $\Lambda$ yield increases faster than the participant scaling expectation for $\nu \leq 3$ and then saturates. The same result has been obtained by BNL E910 Collaboration for $K^0_s$ and $K^+$-mesons emitted in $p+Au$ reaction. Now let us consider some example on nuclear-nuclear interactions.

1.2 Nuclear-Nuclear Interaction

Fig. 3 presents the average values of multiplicity $<n_s>$ for $s$ - particles produced in $Kr+Em$ reactions at 0.95 GeV/nuc as a function of centrality [3]. One can say that there are two regions in the behavior of the values of $<n_s>$ as a function of $N_g$ for the Kr+Em reaction. In the region of: $N_g < 40$ the values of $<n_s>$ increase linearly with $N_g$, here the cascade evaporation model (CEM [4]) also gives the linear dependence but with the slope less than the experimental one; $N_g > 40$ CEM gives the values for average $n_s$ greater than the experimentally observed ones. The last saturates in this region and the effect could not be described the CEM. This has been already observed in emulsion experiments [5].

1.3 Heavy Ion Collisions

It is very important that the regime change has been indicated in the behavior of heavy flavor particles production in ultrarelativistic heavy ion collisions as a function of centrality. The ratio of the $J/\Psi$ to Drell-Yan cross-sections has been measured by NA38 and NA50 SPS CERN as a function of the centrality of the reaction estimated, for each event, from the measured neutral transverse energy $E_t$ [6]. Whereas peripheral events exhibit the normal behaviour already measured for lighter projectiles or targets, $J/\Psi$ shows a significant anomalous drop of about 20% in the $E_t$ range between 40 and 50 GeV. The detailed pattern of the anomaly can be seen in Fig. 4 which shows the ratio of the $J/\Psi$ to
the Drell-Yan cross-sections divided by the exponentially decreasing function accounting for normal nuclear absorption.

Other significant effect seen from this figure is a regime change in the $E_t$ range between 40 and 50 GeV both for light and heavy ion collisions and saturation.

2 Main Results and Discussion

At some values of centrality the regime change and saturation appears as a critical phenomena for hadron-nuclear, nuclear-nuclear interactions and heavy ion collisions in the range of energy from SIS up to RHIC almost for all particles (from mesons, baryons, strange particles up to charmonium). The simple models (such us WN and CEM) which are usually used to describe the high energy hadron-nuclear and nuclear-nuclear interactions could not explain the existence of the point of regime change and saturation. The results show that the dynamics of the phenomena should be same for hadron-nuclear, nuclear-nuclear interactions and heavy ion collisions independent of the energy and mass of the colliding nuclei and the types of particles. The responsible mechanisms to describe the above mentioned phenomena could be statistical and percolation ones because of their critical character. Ref. [7] presented the complicated information about using statistical and percolation models to explain the experimental results coming from heavy ion physics. The regime change and saturation was observed for hadron-nuclear and light nuclear-nuclear interaction where it is very hard and practically impossible to reach the necessary conditions to apply the statistical theory (the statistical models have to give the more strong A-dependencies than percolation mechanisms). Therefore, we believe that the responsible mechanism to explain the phenomena could be the percolation cluster formation [8]-[10]. Big percolation cluster may be formed in the hadron-nuclear, nuclear-nuclear and heavy ion interactions independent on the colliding energy. But the structure and the maximum values of the reaching density and temperature of hadronic matter can be different for different interactions and may depend on the colliding energy and masses in the framework of the cluster. Ref. [11] discusses that deconfinement is expected when the density of quarks and gluons becomes so high that it no longer makes sense to partition them into color-neutral hadrons, since these would strongly overlap. Instead we have clusters much larger than hadrons, within which color is not confined; deconfinement is thus related to cluster formation. This is the central topic of percolation theory, and hence a connection between percolation and deconfinement seems very likely [12]-[14]. So we can see that the deconfinement could occur in the percolation cluster. Ref. [11] explains the charmonium suppression as a result of deconfinment in cluster too.

3 Search for signal

Observation of the effects connected with formation and decay of the percolation clusters in heavy ion collisions at ultrarelativistic energies could be the first step for getting the information about the onset stage of deconfinement. We consider two signals to identify the formation of the intermediate baryon systems:

- the critical change the transparency of strongly interacting matter;
- the enhancement of light nuclei production with the increasing centrality.
3.1 Critical change the transparency of strongly interacting matter

The critical change of transparency can be expected to influence the characteristics of secondary particles. As collision energy increases, baryons retain more and more of the longitudinal momentum of the initial colliding nuclei, characterized by a flattening of the invariant particle yields over a symmetric range of rapidities, about the center of mass - an indicator of the onset of nuclear transparency. To confirm the deconfinement in cluster it is necessary to study the centrality dependence in the behavior of secondary particles yields and simultaneously, critical increase in the transparency of the strongly interacting matter. Appearance of the critical transparency could change the absorption capability of the medium and we may observe a change in the heavy flavor suppression depending on their kinematical characteristics. It means that we have to observe the anomalous distribution of some kinematical parameters because those particles which are from the region with superconductive properties (from cluster) will be suppressed less than the ones from noncluster area. So, the study of the centrality dependence of heavy flavor particle production with fixed kinematical characteristics may give the information about changing of absorption properties of medium. Comparison of yields in different ion systems by using nuclear modification factors such as $R_{CP}$ (involving Central and Peripheral collisions) should provide information on the hadronization \[15\]. $R_{CP}$ highlighted the particle type dependence at intermediate $p_T$ as it was suggested by coalescence models \[16\] leading to the idea that hadrons result from the coalescence of quarks in the dense medium. At high $p_T$, jet fragmentation becomes the dominant process to explain the hadron formation. Hence, the quark constituents may be the relevant degrees of freedom for the description of collision. Using the relation $R_{CP} = \frac{n_1}{n_2}$ (here e.g. $n_1$ and $n_2$ could be heavy flavor particles yields with fixed values of $p_T$ and $\eta$) as a function of centrality, the masses and energy it is possible to get necessary information on the properties of the nuclear matter. With such definition of the $R$, appearance of transparency could be identified and detected using the condition $R \approx 1$. Using the statistical and percolation models \[7\] and experimental data on the behavior of the nuclear modification factors one can get information on the appearance of the anomalous nuclear transparency as a signal of formation of the percolation cluster.

3.2 Enhancement of a light nuclei production

There is a very positive chance that the effect of the light nuclei emission \[17\]-\[20\] in heavy ion collisions are to be one of the accompanying effects of percolation cluster formation and decay. Light nuclei could be formed during the formation of percolation cluster in pressure phase of nucleons before deconfinement and in the phase of QGP expansion and cooling as a result of nucleon coalescence. However, there is one more way of light nuclei formation. It is well known that the light nuclei can be formed mainly as a result of the disintegration of the projectiles and the targets during the interaction. These processes are called nuclear fragmentation and have been studied well. The yields of light nuclei (fragments) in this case have to increase with centrality from peripheral collisions to semicentral ones then the yields have to decrease as is shown in Fig.5 (taken form Ref. \[21\]).

In Fig.5 $Z_{\text{bound}} = \Sigma Z$ for fragments with $Z \geq 2$ emitted in $Au + Au$ collisions at
different energies. Obviously the yields of the d, T, He and other light nuclei need to have almost similar $Z_{bound}$-dependencies. We find it is very interesting to study another way of light nuclei formation, the formation as a result of the recombination of created or stopped nucleons \[22\] (references therein). This recombination process is called coalescence. The probability of coalescence of a particular nuclear system depends on the properties of the hadronic system formed as a result of the collision. So as an effect accompanied by high density nuclear matter - the one under extreme conditions, coalescence could provide us the information about the states of high baryon density nuclear matter. Since the probability of coalescence of a particular nuclear system depends on the properties of the hadronic system formed as a result of the collision, it may be expected that probability of nucleon coalescence process could increase with the growing nuclear matter density. Light nuclei are fairly large objects compared to simple hadrons and their binding energies are small compared to freeze out temperatures, which are of the order 100 MeV. These light clusters are therefore not expected to survive through the high density stages of the collision. The light nuclei observed in the experiment are formed and emitted near freeze-out, and they mainly carry information about this late stage of the collision. This is evident from the simple nucleon coalescence model \[23]-\[24\]. Existing light nuclei produced as a result of coalescence has to change the behavior of the centrality dependences of light nuclei yields. The regime change in the behavior of light nuclei yields as a centrality of collisions is expected. So we believe that studying the yields of light nuclei produced in the heavy ion collisions at relativistic and ultrarelativistic energies as a function of collision centrality could provide the information on formation of intermediate baryon systems in hadron-nuclear and nuclear-nuclear interactions. In experiment the light nuclei produced as a result of nucleon coalescence mechanisms will be separated from other ones using the following idea. The yields of the light nuclei produced as a result of disintegration of the projectiles and the targets during the interaction will behave as in Fig.5. Appearance of light nuclei formed as a result of nucleon coalescence phenomenon can be a reason of the regime change in the behavior of light nuclei yields.

It could be the first step of testing the idea and the second step is to get some confirmation about the mechanism of the cluster formation. To confirm that percolation mechanism could be a single reason of the cluster formation it is necessary to show that the regime change of the behavior of light nuclei yields as a function of the centrality had a critical character and may be observed also for the nuclei target (and projectile) with small atomic masses.

4 Summary

Therefore the centrality experiments indicate the critical appearance of the regime change and saturation in the behavior of some characteristics of the secondary particles emitted in hadron-nuclear and nuclear-nuclear interactions at high energies. The underling mechanism to explain the phenomena could be the formation and decay of the intermediate baryon systems which may form as a result of nucleon percolation in compression baryonic matter. The critical changing of transparency of the strongly interacting matter and the enhancement of the yield of light nuclei production with centrality could be considered as two signals to identify the formation of the intermediate baryon systems.
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Figure 1: The average multiplicity of the $\pi^-$-mesons produced in proton-Be, Cu, and Au collisions as a function of centrality at a beam momentum of 18 GeV/c. Solid line demonstrates the results coming from the WN-model.

Figure 2: The $\Lambda$ yield versus $\nu$ (see text).
Figure 3: The average values of multiplicity $< n_s >$ for $s$ - particles produced in $Kr + Em$ reactions at 0.95 GeV/nucl as a function of centrality.

Figure 4: The ratio of the $J/\Psi$ to the Drell-Yan cross-sections divided by the exponentially decreasing function accounting for normal nuclear absorption.

Figure 5: