ON THE MIXED PHASE OF STRONGLY INTERACTING MATTER

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1. Introduction.

The studying of the behavior of some characteristics of hadron-nuclear and nuclear-nuclear interactions as a function of the collision centrality Q is an important experimental method to get information about the changes of nuclear matter phase, because the increasing of the centrality could lead to the growth of the nuclear matter baryon density. In other words, the regime change in the behavior of some centrality depending characteristics of events is expected by the varying the Q. It would be the signal about the phase transition. This method is considered as the best tool reaching the quark-gluon plasma phase of strongly interacting matter.

Some experimental results demonstrate already the existence of the regime changes in the event characteristics behavior as a function of collision centrality.

Let us look over some of them[1].

First results of hadron -nuclear reactions.

In paper [1] the results are presented 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. The centrality of the collisions is characterized using the measured number of «grey» tracks, N_{grey} , and a derived quantity, ν, the number of inelastic nucleon-nucleon scatterings suffered by the projectile during the collision. The values of average multiplicity for π^-- mesons (<π^--Multiplicity>) as a function of N_{grey} and ν for the three different targets are plotted in Fig. 1.

We see that the <π^-- Multiplicity> increases approximately proportionally to N_{grey} and ν for all three targets at small values of N_{grey} or ν and saturates with increasing of N_{grey} and ν in the region of more high values of N_{grey} and ν. It is also shown with a solid line in Figure the expectations for the <π- Multiplicity> (ν) based on the wounded - nucleon (WN) model and with dashed line, does a much better job of describing p-Be yields than the WN model. So the results demonstrate definitely the regime changes of the behavior for these distributions. BNL E910 has measured the Λ production as a function of collision centrality for 17.5 GeV/c p–*A*u collisions [2]. Collision centrality is defined by *ν*. The Λ yield versus *ν* is plotted in Fig.2(5). The open symbols are the integrated gamma function yields. The black symbols are the fiducial yields. The various curves represent different functional scalings. We see that the measured Λ yield increases for $\nu \leq 3$ and then it saturates with increasing *ν*. Similar results for K^+-, K^0_s - mesons and Ξ^- multiplicity in p+Au collision at 17.5 GeV/c have also been obtained by the BNL E910.

The results on the nuclear-nuclear reactions.

In paper [3] the experimental results of particle multiplicity distributions in silicon-emulsion collisions at 4.5*A* GeV/*c* are reported. The correlations between the multiplicities of target fragments are given. The saturation effect of target black fragment multiplicity in the collisions is observed. It is demonstrated in Fig. 3 where the dependence of $\langle N_b \rangle$ on N_g for silicon-emulsion collisions at 4.5*A* GeV/c (closed circles) is presented. The corresponding results for oxygen-emulsion collisions at 3.7*A* GeV (open circles) and 200*A* GeV (open squares) are given in the figure, too. One can see that the value of $\langle N_b \rangle$ increases with the increasing N_g in the region of $N_g<8$, and the saturation effect appears in the region of $N_g>8$. The saturation effect was previously observed in proton-emulsion collisions at high energy [4]. Recently, in oxygen-emulsion collisions at the Dubna and SPS energies, the saturation effect was also observed [5].

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[1] It is necessary to note that the number of identified protons (N_p), fragments (N_F), slow particles (N_{slow}), of h - and g - particles (N_h and N_g accordingly in emulsion experiments) have been used to obtain information on the Q and correspondingly on the impact parameter of the collision.The measured energy flow of the particles at an emission angles $\theta=0^0$ and $\theta=90^0$ have also been used to define the Q. Apparently, it is not simple to compare quantitatively the results on Q-dependencies of event characteristics taken from different papers.

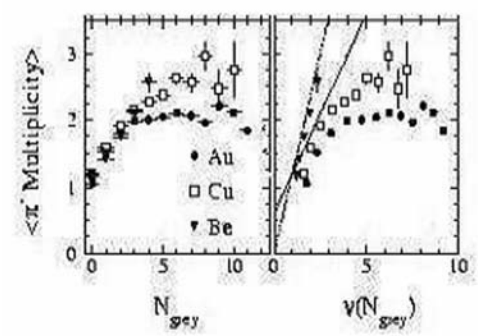


*Fig.1.*The values of average multiplicity for π^- - mesons ($<\pi^-$ Multiplicity>) as a function of N_{grey} and ν for the three different targets. Solid line in figure is expectations for the $<\pi^-$ Multiplicity> (ν) based on the wounded -nucleon (WN) model and the dashed line, does a much better job of describing p-Be yields than the WN model.

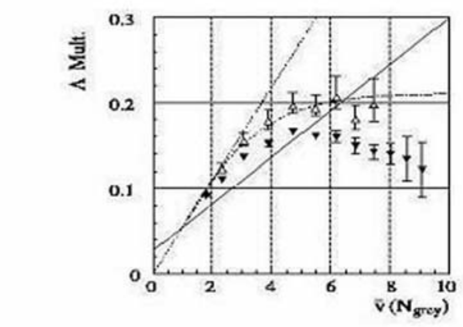


Fig.2 Λ production as a function of collision centrality for 17.5 GeV/c p–*A*u collisions. The open symbols are the integrated gamma function yields. The black symbols are the fiducial yields. The various curves represent different functional scalings.

In paper [6] the results are presented on dimuon production in proton-tungsten and sulphur-tungsten interactions at 200 GeV/*c*/nucleon were measured using the HELIOS/3 dimuon spectrometer at the CERN SPS. It was made a direct experimental comparison between the S-W and p-W results for the ratio $\mu\mu$/charged particles and found there was a clear excess in $\mu\mu$ production relative to charged particle production in S-W interactions compared to p-W interactions as a function of mass. The excess is defined as the difference between S-W and p-W spectra. The values of inverse slope parameter of the transverse mass distribution for low mass excess versus of the charged multiplicity is shown in next Fig. 4. We can also see the regime change in the behavior of this distribution.

The ratio of the J/ψ to Drell-Yan cross-sections has been measured by the CERN NA50 as a function of the centrality in Pb-Pb collision at 158 GeV/nucl [7]. It is shown in this Fig.5. E_T fixes the centrality, which was a transverse energy flow. The result for light nuclei collisions is also demonstrated with solid line in the figure. The regime change is observed for the behavior of these dependencies.

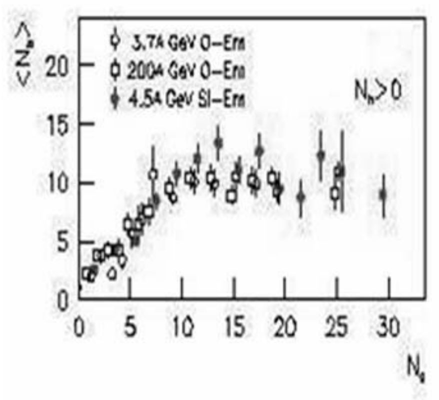


Fig. 3 The dependence of <Nb> on Ng for silicon-emulsion collisions at 4.5*A* GeV/c (closed circles). The corresponding results for oxygen-emulsion collisions at 3.7*A* GeV (open circles) and 200*A* GeV (open squares) are given in the figure, too.

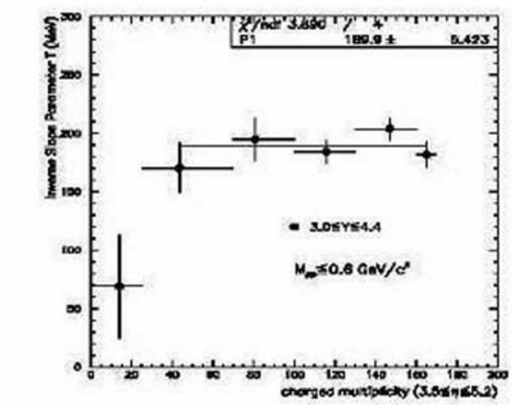
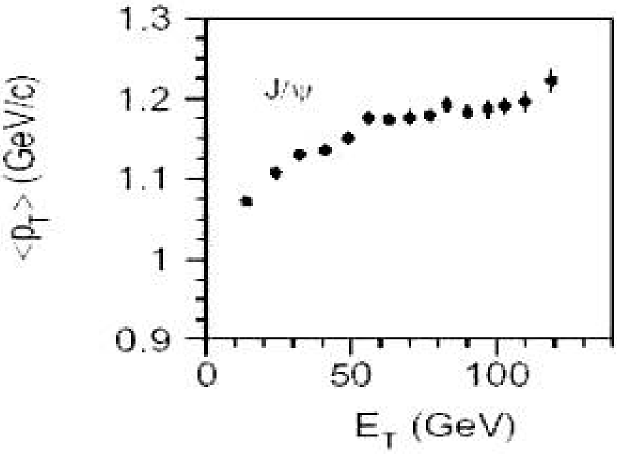


Fig. 4 The values of inverse slope parameter of the transverse mass distribution for low mass excess versus of the charged multiplicity production in proton-tungsten and sulphur-tungsten interactions at 200 GeV/*c*/nucleon.



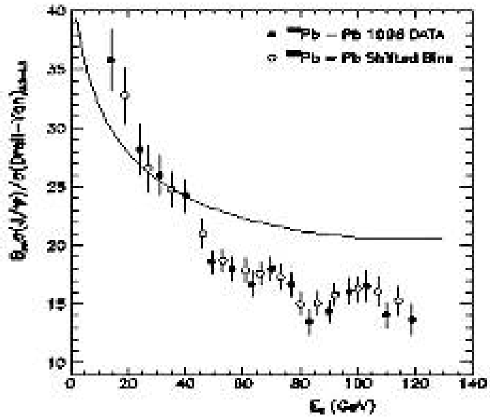


Fig.5 The ratio of the J/ψ to Drell-Yan cross-sections as a function of the centralityin Pb-Pb collision at 158 GeV/nucl .

Fig. 6 $<P_t>$ as a function of the transverse energy for J/Ψ mass intervals. The error bars are only statistical.

In paper [8] the moon pairs produced in Pb-Pb interactions at 158 GeV/*c* per nucleon are used to study the transverse momentum distributions of the J/Ψ , Ψ' and dimuons in the mass continuum. In particular, the dependence of these distributions on the centrality of the Pb-Pb collision is investigated in detail.
The $<P_t>$ values obtained for the J/Ψ are plotted in Fig. 6 as a function of E_T. It is seen for the J/Ψ , the values of $<P_t>$ first increase and then tend to flatten when the centrality of the collision increases.

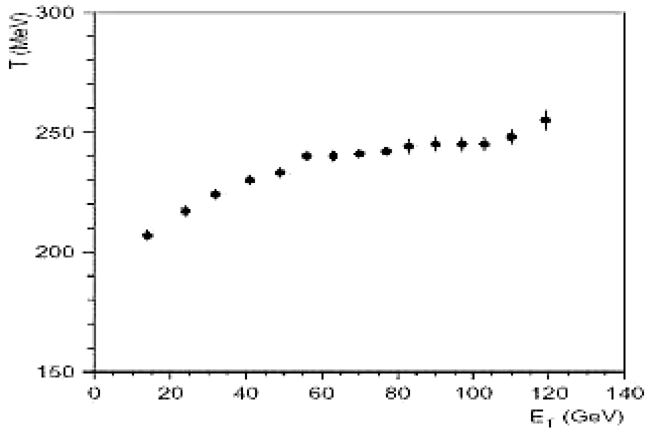


Fig. 7 Inverse slope parameter, T, of the J/Ψ transverse mass distributions, plotted as a function of the transverse energy.

The transverse mass distributions of the produced muon pairs have also been studied in order to allow a comparison with thermal models. The inverse slope T of J/Ψ transverse mass distributions is also plotted in Fig. 7 as a function of the E_T. First it increases with E_T and then seem to flatten at high E_T, as the $<P_t>$ values.

So the main obtained result is the existence of the regime changes. The regularity is observed for hadron-nuclear and nuclear-nuclear interactions as well for the interaction of light and heavy nuclei; at high and at low temperature; and for the π-mesons, nucleons, fragments (F), strange particles (S) and J/Ψ, that is the regularity is also observed at small densities and temperatures. Therefore it could not be connected with the existing of the predicted QCD point for hadronic matter quarks-gluons phase transition.

2. The Mixed Phase

Therefore it was suggested to consider the appearance of the strongly interacting matter mixed phase (MP) for a qualitative understanding of the regularity. MP is considered as a phase of compressed nucleons. These phase are predicted by QCD for the temperatures around the critical temperature T_c . It could be formed in the result of nucleon percolation in density nuclear matter. It is well known the statistical and percolation theories can describe the critical phenomena best of all. But how we have seen the regime changes have also been observed for small density and temperature for which the conditions of applying of statistical theories are practically absent. So the percolation approach could be the only approach for the description of the results. Therefore we consider the percolation mechanisms as one of the mean mechanisms for MP formation. It would lead to the formation of the percolation cluster.
In paper [9] was discussed that percolation clusters much larger than hadrons, within which color is not confined; deconfinement is thus related to percolation cluster formation. This is the central topic of percolation theory, and hence a connection between percolation and deconfinement seems very likely [10-12]. So percolation cluster can be color object.

Therefore MP could be considered as a system of color and color-neutral objects and experimental information on the particular conditions of the MP formation is important for the fix the onset stage of deconfiment.

2.1.Experimental signals on Mixed Phase

To experimental confirmation the MP formation it is necessary to extract the signals on the accompany effects of MP. We can say that the effects of cluster formation, the appearance of critical nuclear transparence and the π-meson condensate could be the accompany ones.

3.1 Effect of percolation cluster formation.

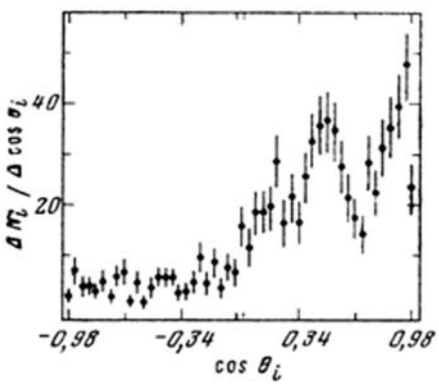


Fig. 8 Angular distributions of protons emitted in $\pi^{-12}C$ -interactions at momentum 40 GeV/c

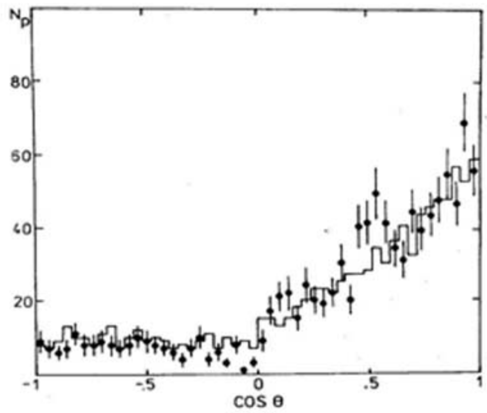


Fig. 9 Angular distributions of protons emitted in $\pi^{-12}C$ -interactions at. the momentum 5 GeV/c.

The cluster could be form in the result of percolation of nucleons in high-density baryon system. There are many papers in which the processes of nuclear fragmentation [13] and the processes of central collisions [14] are considered as critical phenomena and it is suggested that the percolation approach to be used to explain these phenomena. We suppose that the cluster had formed at some critical values of Q in hadron-nucleus and nucleus-nucleus collisions and then with increase of Q it would decay on fragments and free nucleons.

The existence of the percolation cluster could explain the experimental results on the angular distributions of emitted protons in $\pi^{-12}C$ -interactions at the momentum 40 GeV/c [15]. In these experiments the angular distributions of protons (with the momentum less than 1.0 GeV/c) were studied in the events with total disintegration of nuclei (or central collisions). This distribution is shown in Fig.8. The anomalous peak in this distribution is seen. The results on the angular distributions of protons emitted in $\pi^{-12}C$ -interactions at momentum 5 GeV/c [16] confirm the existence of the anomalous peak (Fig.9). We believe that it could be connected with formation and decay of the percolation cluster. The anomalous peak in angular distribution of emitted protons and fragments could be considered as the signal of the percolation cluster and MP formation (signal I).

3.2 Effect of critical nuclear transparence

When the MP appears the conduction of nuclear mutter could sharply increase and the matter could become a superconductor [9] because the nucleons must be bound in the result of percolation in high-density baryon system. It could lead to critical change of the angular correlation of particle production and might be another signal on MP formation (signal II).

3.3 Effect of π-meson condensation

The meson condensate appearance effect might be the other accompanying effect for the processes of MP formation. The idea of a meson condensate formation was predicted [17] many years ago. But up to now there are no experimental results definitely confirming this idea. When we analyzed the results from the TAPS setup [18] we found some results, which could be interesting for the experimental search of the meson condensate. In these papers the temperature of the slow π^0 -mesons defined as slopes of the invariant transverse mass (m_t) spectrum, which are shown in Fig.10 - 11. The result at low m_t is to be very interesting as the behavior of the m_t-spectrums differ from the exponential law (in Fig. 10). We believe that some part of these deviations could be connected with the appearance of meson condensate. It depends on the centrality (Fig.11). The last is the main argument confirming that the observed deviation could be connected with the meson condensate. The centrality dependence of this deviation could be considered as one more signal on MP formation (signal III).

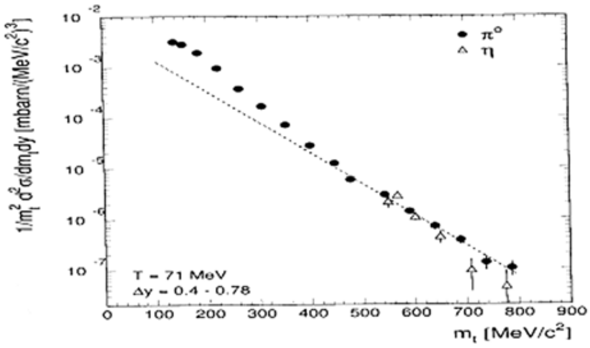


Fig.10 Transverse-mass spectra of π^0 and η-mesons for Au+Au interactions at 0.8 A MeV.

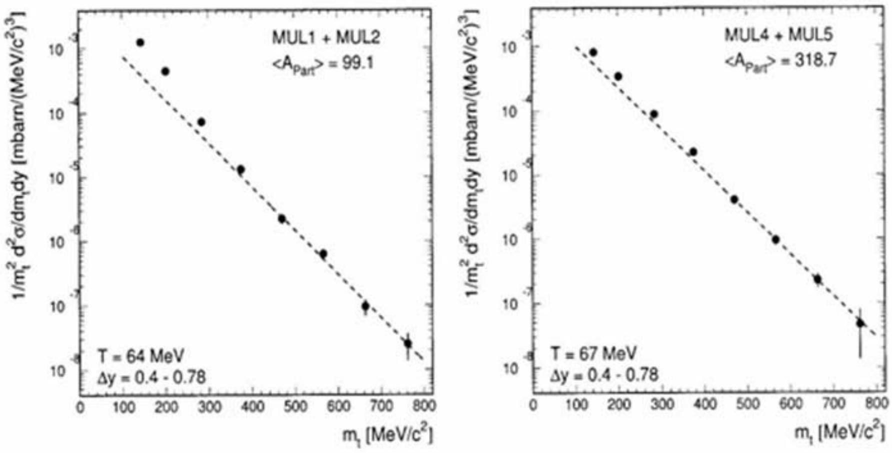


Fig.11. Transverse-mass spectra of π^0 and η-mesons for Au+Au interactions at 0.8 A MeV in:
a) noncentral collisions; b) in central collisions.

4. Conclution

So we think that the simultaneous observation of signals I-III could all low to get an important information for answer of the question on MP formation. Therefore we are going to investigate the behavior of angular distributions of protons; a behavior of π^0- or π^++π^--mesons pair invariant spectrum as a function of the m_t ; the particles yield at different emission angle as a function of the centrality.

We expect to see a simultaneous appearance of the signals I-III.

[1] *Chemakin* et al. The BNL E910 Collaboration, E-print:nucl-ex/9902009 v1, 19, Feb 1999, 3
[2] *Ron Soltz* for the E910 Collaboration. J. Phys. G: Nucl. Part. Phys. 27 (2001) 319–326
[3] *Fu-Hu Liu* et al. Phys. Rev. C 67, 047603(2003)
[4] *Abduzhamilov* et al., Z. Phys. C 40, 223 (1988)
[5] *F.H. Liu*, Chin. J. Phys. (Taipei) 40, 159 (2002)
[6] *A.L.S. Angelis* et al. Eur. Phys. J. C 13, 433-452 (2000) The HELIOS/3 Collaboration.
[7] *M.C. Abreu* et al. Phys.Let. B450,1999,456; M.C. Abreu et al. Phys.Let.B410,1997,337; M.C. Abreu et al. Phys.Let. B410,1997,327
[8] *M.C. Abreu* et al. By NA50 Collaboration : Phys.Lett.B499:85-96,2001
[9] *H.Satz*. E-print:hep-ph/0007069 v1 7 Jul 2000
[10] *H.Satz*, Nucl. Phys. A 642 (1998) 130c.
[11] *G. Baym*, Physica 96 A (1979) 131.
[12] *T. Celik, F. Karsch* and *H. Satz*, Phys. Lett. 97 B (1980) 128. J. Desbois, Nucl. Phys. A466 (1987) 724 ; J. Nemeth et al. Z.Phys.A 325 (1986) 347;
[13] *S. Leray* et al. Nucl. Phys.A511(1990)414; *A.J. Santiago* and *K.C. Chung* J. Phys. G:Nucl.Part. Phys. 16 (1990)1483; *G.Musulmanbekov*, *A.Al-Haidary*.Russian J.Nuc.Phys.,v.66 (2003) 1.
[14] *X.Campi, J. Desbois* Proc. 23 Int. Winter Meeting on Nucl. Phys. Bormio,1985; Bauer W. et al. Nucl. Phys. 452(1986) 699; *A.S. Botvina, L.V.Lanin. Sov. J.* Nucl. Phys. 55 (1992) 381.
[15] *A.I.Anoshin* et al.Yad.Fiz.33:164(1981)
[16] *O.B.Abdinov* et al. Preprint JINR,1-80-859,Dubna (1980)
[17] *A.B.Migdal*, Zh ETF (USSR) 61(1971),2210 Jetp (Sov.Phys) 34 (1972) 1184; Zh ETF (USSR) 63(1972),1933 JETP (Sov.Phys) 36 (19730,1052; R.F. Sawyer, Phys.Rev.Lett.29 (1972),382 ;D.J. Scalapino, Phys.Rev.Lett. (1972),386; *R.F. Sawyer* And *D.J. Scalapino*, Phys.Rev.D7(1972),953.
[18] *R. Averbeck* et al. Z.Phys.A359:65-73,1997 ; *A. Marin* et al. Phys.Lett.B409:77-82,1997 ; *A.R.Wolf* et al. Phys.Rev.Lett. Vol.80,N 24,P.5281; *A. R. Wolf* , Doktorarbeit, Gieben 1997