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The hadron production in π^--C interaction at 40 GeV/c and QCD phase transition

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Abstract. In this paper, we proposed to study the phase transition process to use the new pair of variables, the temperature T and the cumulative number n_c (T,n_c). We considered the transverse energy spectra of protons and π^--mesons produced in π^--C interactions at 40 GeV/c as a function of cumulative number n_c (or four-dimensional momentum transfer t) and the baryonic chemical potential $\mu_b(\sqrt{t})$. Obtained results indicate the possible appearance of QCD phase transition of nuclear matter.

1 Introduction

Quantum chromodynamics (QCD) is the fundamental theory of the strong interaction and this is an asymptotically free theory [1,2] i. e. interactions between quarks and gluons become weaker as the mutual distance decreases or as exchanged momentum increases. Consequently at large temperatures and /or densities, the interactions which confine quarks and gluons inside hadrons should become sufficiently weak to release them [2].

There is hope that the QCD phase transition processes may be realized in the hadron-nucleus and nucleus-nucleus interactions at high energies and large momentum transfers and in the astrophysical objects of very high density such as neutron stars.

During the last years the collective phenomena such as the cumulative particle production [4], the production of nuclear matter with high densities, the phase transition from the hadronic matter to the quark-gluon plasma state and color-superconductivity is widely discussed in the literature [3-6, 11-17].

According to the different ideas and models, if these phenomena exist in the nature, then they will be observed in the hadron-nucleus and nucleus-nucleus interactions at high energies and large momentum transfers and should be influenced to the dynamics of interaction process and would be reflected in the angular and momentum characteristics of the reaction products.

The present status of the QCD phase diagram is shown schematically in figure 1. This figure was taken from [12].

Running coupling constant of QCD:

$$\alpha_s(Q^2) = \frac{1}{\beta_0 \ln \frac{Q^2}{\Lambda^2}}, \qquad \beta_0 = \frac{1}{4\pi}\left(11 - \frac{2}{3}n_f\right) \tag{1}$$

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where Q^2 is momentum transfer square and Λ is the cut parameter. If parameter $T \geq \Lambda \approx 200$ MeV, QCD predicts the phase transition from hadronic state to QGP.

According to the theoretical investigations, the strongly interacting matter depending on the temperature and the density may occur in the next different phases: the hadronic phase, the mixed phase (h+QGP),the quark-gluon plasma (QGP) and color-superconducting quark matter [3, 5, 11, 12, 14-17].

For temperatures below $T_c \approx 200$ MeV and below nuclear matter density ρ, corresponding to net-baryon densities which are a few times greater than the ground state density of nuclear matter, the strongly interacting matter is in the hadronic phase. There is a line of the phase transition (the mixed phase) which separates the hadronic phase from the QGP. Finally, at large temperatures $T > T_c$ and densities the nuclear matter is in the QGP state. There is also the theoretical prediction about the existence of the color superconducting phase at comparatively small temperature and large baryon densities [14-17].

According to the color superconducting theory of QCD, the critical temperature T_c to color superconducting phase is described by the next formula [14-17]

$$T_c \cong 0.57 \cdot \Delta \cong 50MeV, \tag{2}$$

where Δ is the gap energy and the magnitude of this parameter, the fundamental energy scale that characterizes color superconductivity. The value of the color-superconducting gap parameter Δ is therefore of great importance in order to locate the transition line between the normal nuclear matter and the color-superconducting quark matter phases in the nuclear matter phase diagram.

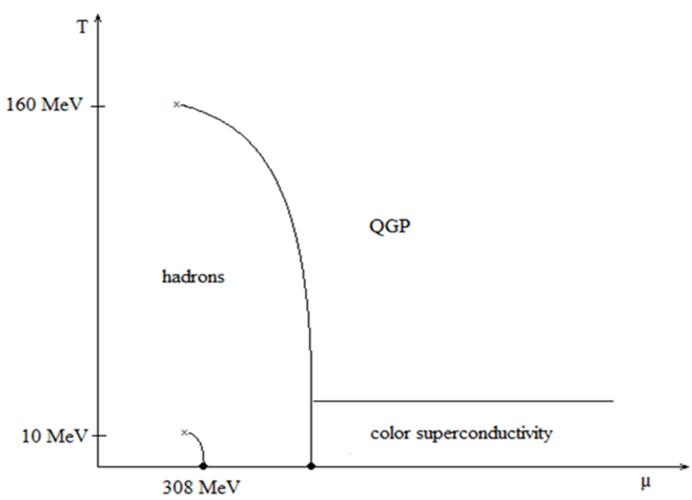

Figure 1. The phase diagram of strongly interacting matter (schematic).

The different model calculations [12, 14-17] yield predictions for the gap parameter Δ and critical temperature T_c. The energy gaps Δ are of order of 10 MeV to 100 MeV, with critical temperature about half as large ($T_c \sim 50MeV$).

The investigation of the multiparticle production process in hadron-nucleus and nucleus-nucleus interactions at high energies and large momentum transfers is very important for understanding the strong interaction mechanism and inner quark-gluon structure of nuclear matter.

In this paper we are considered the next reactions:

$$\pi^- C \rightarrow p + X \tag{3}$$

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$$\pi^- C \to \pi^- + X. \tag{4}$$

This paper is a continuation of our previous publication [6,7].

2 Variables Used

2.1 Cumulative number

The cumulative number n_c in the fixed target experiment is determined by the next formula:

$$n_c = \frac{P_a \cdot P_c}{P_a \cdot P_b} \cong \frac{E_c - \beta_a p_{\parallel}^c}{m_p}. \tag{5}$$

Here P_a, P_b and P_c are the four-momenta of the incident particle, target and the considered secondary particles, respectively. E_c is the energy and $p_{\parallel}^c$ is the longitudinal momentum of the considering particle, $\beta_a = \frac{p_a}{E_a}$ is the incident particle velocity, m_p is the proton mass. From this formula we see that this variable is a **relativistic invariant** and n_c is the value of the target mass which is required for production of the secondary particle.

The connection of the variable n_c and momentum transfer t is determined by the next formula [7]:

$$t = -Q^2 = -(P_a - P_c)^2 \cong 2E_a \cdot \frac{m_p}{m_p} \cdot (E - p_{\parallel}) - (m_a^2 + m_c^2) = S_{\pi^- p} \cdot n_c - (m_a^2 + m_c^2), \tag{6}$$

where $S_{\pi^- p} \simeq 2E_a \cdot m_p$ is the total energy squared of $\pi^- p$ interaction.

2.2 The baryonic chemical potential $\mu_b(\sqrt{t})$ as a function of the transferred momentum t

The paper [19] showed that the baryonic chemical potential μ_b(MeV) as a function of energy S_{NN} is parameterized by the following formula:

$$\mu_b(\sqrt{S_{hN}}) = \frac{1.303 GeV}{1 + 0.286 GeV^{-1} \sqrt{S_{hN}}}. \tag{7}$$

Then using the formula (6) which gives the connection between n_c, $S_{hN} \approx 2E_a m_p$ and transferred momentum t, we have a possibility to do the similar parameterization of the baryonic chemical potential $\mu_b(t)$ as a function of the transferred momentum t by the equation:

$$\mu_b(\sqrt{t}) = \frac{1.303 GeV}{1 + 0.286 GeV^{-1} \sqrt{t}} = \frac{1.303 GeV}{1 + 0.286 GeV^{-1} \sqrt{2E_a m_p n_c - (m_a^2 + m_c^2)}}, \tag{8}$$

where E_a and m_a are the incident particle energy and mass, n_c and m_c are the cumulative number and mass of the secondary particles.

Note that using formula (8) one can calculate values of $\mu_b(\sqrt{t})$ which belong to the secondary particles, in other words, this formula gives us a possibility to study the behaviour of the parameter T as a function of $\mu_b(\sqrt{t})$ using experimental data obtained in one experiment.

2.3 The effective temperature T

The transverse energy spectra of the secondary particles in the different n_c intervals are approximated by exponential function of the next form:

$$\frac{1}{2 \cdot E_t} \frac{\Delta N}{\Delta E_t} \sim e^{-bE_t}, \qquad E_t = \sqrt{p_t^2 + m^2}. \tag{9}$$

The effective temperature T is determined as the inverse slope parameter b:

$$T = \frac{1}{b}. \tag{10}$$

3 Experimental method

The experimental material was obtained with the help of the Dubna 2-meter propane (C_3H_8) bubble chamber exposed by π^-- mesons with momentum 40 GeV/c from Serpukhov accelerator. According to the advantage of the bubble chamber experiment all distributions in this paper are obtained under the condition of 4π geometry of secondary particles.

The average error of the momentum measurements is ~ 12% and the average error of the angular measurements is ~ 0.6^o.

All secondary negative particles are taken as π^--mesons. The average boundary momentum from which π^--mesons were well identified in the propane bubble chamber is ~ 40 MeV/c. In connection with the identification problem between energetic protons and π^+-mesons, protons with momentum more than ~ 1 GeV/c are included to the π^+-mesons. The other experimental details are described in [8, 9].

4 Statistics

8791 π^-C interactions are used in this analysis.

1. The total number of protons is 12441
2. The total number of π^- mesons is 30145.

5 Experimental results

The temperature (T) dependencies for secondary π^--mesons and protons from π^-C–interactions at 40 GeV/c as a function of the variable n_c (or t) are shown in figures 2, 3. From figure 2 we see that with increasing n_c the parameter T is increasing up to $n_c \cong 0.07$ and then in the $0.07 \leq n_c < 0.5$ interval the parameter T remains practically constant on the level $T \cong (0.233 \pm 0.004)$GeV and then again increases [13].

The corresponding dependence obtained for protons shows that the parameter T remains constant on the level $T_c \cong 50$ MeV in the $0.5 < n_c < 1.2$ interval and then increases.

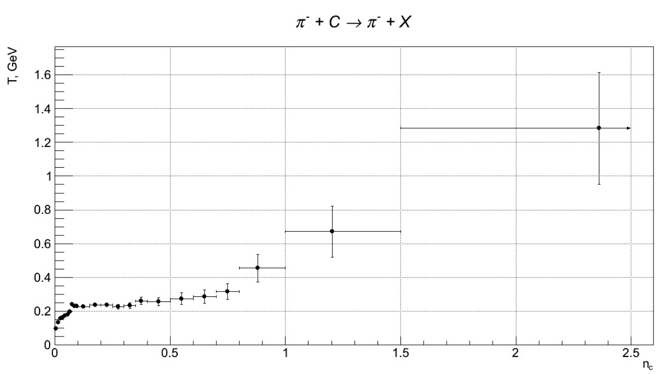

Figure 2. The dependence of the temperature T of π^-–mesons on cumulative number n_c from π^-C interactions at 40 GeV/c

So we observe the essential change of the behavior of the parameter T of protons and π^-–mesons in π^-C interactions at 40 GeV/c on the variable n_c in two different regions for protons and in three different regions for π^-–mesons. Such behavior may indicate the particle production different mechanism in these ranges of the variable n_c (or t) and temperature T. If so, the I region in which the

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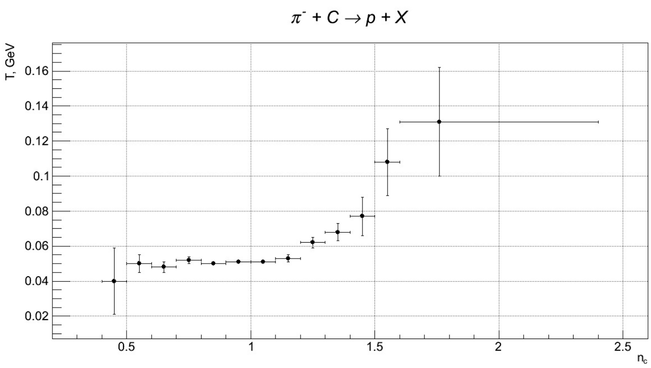

Figure 3. The dependence of the temperature T of protons on cumulative number n_c from $\pi^- C$ interactions at 40 GeV/c

temperature T increases for π^-–mesons may be connected with the thermalization of the strongly interacting objects. In this region the strongly interacting matter is in the hadronic phase.

In the II regions where the temperature T remains practically constant, the strongly interacting matter is in the thermodynamical equilibrium state (or the mixed phase).

In the III regions where the parameter T increases again, the strongly interacting matter is in the QGP phase.

We would like to note that this value of the critical temperature T_c, obtained for protons is in agreement with the theoretical prediction $T_c \cong 50$ MeV for the color-superconductivity of QCD [12, 14].

As mentioned above, the theoretical prediction of the critical temperature T_c for the color-superconductivity of QCD was obtained in the region of the phase diagram with high density and low temperature. Our experimental result also corresponds to this region.

From formula (8) we see that the baryonic chemical potential $\mu_b(\sqrt{t})$ is inversely proportional to the variable n_c and its numerical values are determined by n_c (or t).

So, the dependence of the parameter T on the variable $\mu_b(\sqrt{t})$ should give the inverse dependence (see figure 4, 5) in comparison with T dependencies as a function of n_c (see figure 2, 3).

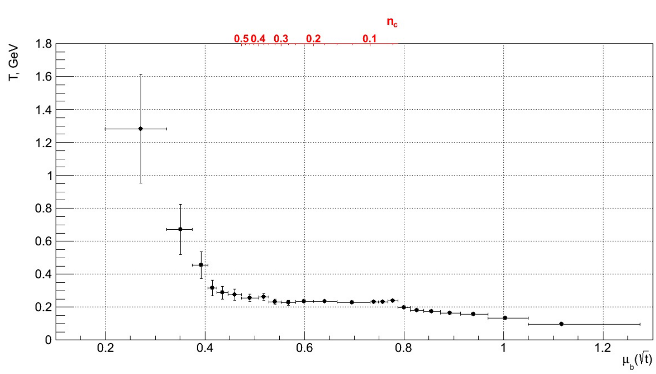

Figure 4. T dependence of π^--mesons as a function of the baryonic chemical potential $\mu_b(\sqrt{t})$ from $\pi^- C$ interactions at 40 GeV/c

Figure 6,7 show dependencies of the average values of the transverse momentum squared $\langle p_T^2 \rangle$ of π^--mesons and protons on the variable n_c. With increasing n_c the $\langle p_T^2 \rangle$ increases and then in the $0.07 < n_c < 0.5$ interval for π^--mesons and in the $0.5 < n_c < 1.2$ interval for protons remain practically constant and then again increases.

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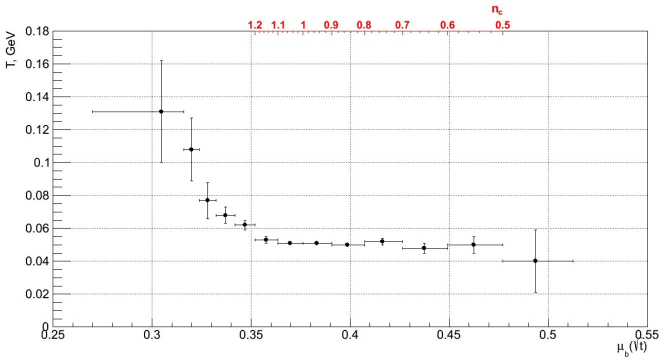

Figure 5. T dependence of protons as a function of the baryonic chemical potential $\mu_b(\sqrt{t})$ from $\pi^- C$ interactions at 40 GeV/c

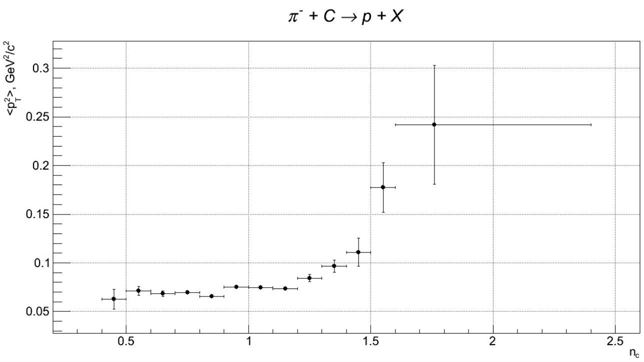

Figure 6. The dependence of the average values of the transverse momentum squared $\langle p_T^2 \rangle$ of protons on the variable n_c.

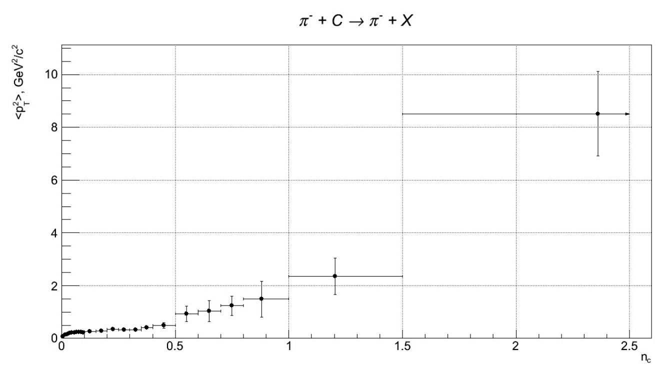

Figure 7. The dependence of the average values of the transverse momentum squared $\langle p_T^2 \rangle$ of π^--mesons on the variable n_c.

We would like to note that dependencies of the parameters T and $\langle p_T^2 \rangle$ as a function of cumulative number n_c of the secondary particles from $\pi^- C$ interaction have very similar behaviour, in other words, these two dependencies have the n_c-regions with constant temperature. This similarity of these two dependencies may be connected with the saturation of the transverse momentum at equilibrium state.

In papers [22, 23], the dependence of $\langle p_T^2 \rangle$ on the cumulative number X of the secondary protons from p+A interactions at 10.14 GeV/c is considered. The result of this study is presented in figure 8. We note that the obtained dependence is in agreement with our result.

In papers [20, 21], the behavior of the phase transition process is determined in the following form:

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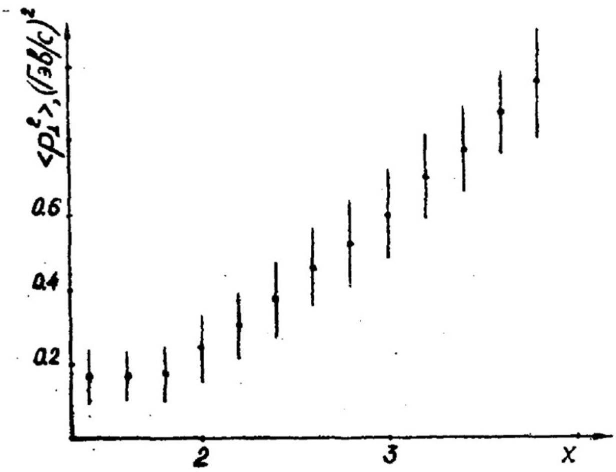

Figure 8. The dependence of $\langle p_T^2 \rangle$ on the cumulative number X [22, 23].

If a phase transition occurs (i.e. a rapid change of the number of degrees of freedom) one expects a monotonously rising curve interrupted by a plateau. This plateau is caused by the saturation of $\langle p_T \rangle$ in mixed phase. After the phase transition from e.g. color singlet states to colored constituents has been completed [20, 21] the mean transverse momentum rises again. Our experimental results are consistent with this statement.

6 Conclusions

- The analysis carried out in this paper gives us the possibility to study the phase transition process of nuclear matter.
- The T dependence of π^--mesons from $\pi^- C$ interactions at 40 GeV/c as a function of cumulative number n_c (or t) and the baryonic chemical potential $\mu_b(\sqrt{t})$ are in agreement with the QCD prediction on the phase transition from hadronic matter to QGP state.
- The baryonic chemical potential $\mu_b(\sqrt{t})$ is expressed by the variable n_c. So, these two variables $\mu_b(\sqrt{t})$ and n_c may be used with equal rights in order to study the phase transition process in hA and AA interactions at high energies.
- The experimental results obtained for the secondary protons produced in the target fragmentation region from $\pi^- C$ interactions at 40 GeV/c don't contradict to the prediction of $T_c \cong 50$ MeV for the color superconducting phase transition of QCD at large density and small temperature but the more detailed analysis is required for this case.

Acknowledgement

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