Half masses of particles produced in $\pi^- C$ interaction at 40 GeV/c and phase transition

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Dubna, 2018

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Introduction

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

According to the fundamental theory of the strong interaction, QCD [1], the interactions between quarks and gluons become weaker as the mutual distance decreases or as the exchanged momentum increases. Consequently, its high temperature and high baryon density phases are appropriately described in terms of quarks and gluons as degrees of freedom, rather than hadrons.

During the last years, the collective phenomena such as the cumulative particle production, the production of nuclear matter with high densities, the phase transition from the hadronic matter to the **quark-gluon plasma** (QGP), and **color superconductivity** are widely discussed in the literature [2]-[6].

To find the critical point E, theorists in the lattice QCD calculations use the strange quark mass m_s [2]. Their theoretical motivation is the following: if they could vary m_s, they would find that as m_s is reduced from infinity to m_s^c, the critical point E can be found. But the value of m_s is an open question [2]. The critical point E is at some nonzero T_E and μ_E. According to the papers [2, 5, 6] if the phase transition occurs, the next features should be observed in dependencies of the multiparticle production process at high energies;

- Signatures are non-monotonic as a function of the control parameters (for example m_s, $\sqrt{S_{NN}}$, n_c): as the control parameter is varied, we should see the signatures strengthen and then weaken again as the critical point is approached and then passed [2].
- if a phase transition occurs (i.e. a rapid change in the number of degrees of freedom) one expects a monotonously rising curve interrupted by a plateau: This plateau is caused by the saturation of $< p_T >$ during the mixed phase. After the phase transition from e.g color singlet states to colored constituents has been completed the mean transverse momentum rises again [5, 6].

We note that the observation of the critical point of the phase transition process from the hadronic phase, the QGP state through the mixed phase is one of the key issues [2, 5, 6] of the multiparticle production process. This paper is devoted to this problem.
In this paper, we consider the following reactions:

$$\pi^- + C \longrightarrow p + X \tag{1}$$

$$\pi^- + C \longrightarrow \pi^- + X \tag{2}$$

$$\pi^- + C \longrightarrow K^0 + X \tag{3}$$

at 40 GeV/c. This paper is the continuation of our previous publications [1, 2, 3, 4].

Experimental method

The experimental material was obtained by means of the Dubna two meter propane (C_3H_8) bubble chamber exposed to π^- mesons with a momentum of 40 GeV/c from Sepukhov accelerator. All distributions in this paper have been obtained under the condition of 4π geometry. The average error of the momentum measurements is $\sim 12\%$, and the average error of the angular measurements is $\sim 0.6\%$.

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 ~ 70 MeV/c. In connection with the identification problem between energetic protons and π^+ mesons, the protons with a momentum more than ~ 1 GeV/c are included into π^+ mesons. The average boundary momentum from which protons are detected in this experiment is ~ 150 MeV/c. So, the secondary protons with momentum from ~ 150 MeV/c to ~ 1 GeV/c are used for proton distributions.

8791 $\pi^- C$ interactions have been used in this analysis. 12441 protons and 30145 π^--mesons have been detected in these interactions. 5800 $\pi^- C$ interactions with the detection of neutral particles have been used for K_0 analysis, 554 K_0 mesons have been detected and used in this analysis.

Dependences of the effective temperature T as a function of the cumulative number n_c

$$n_c = \frac{(P_a \cdot P_i)}{(P_a \cdot P_b)} = \frac{E_i - \beta_a p_i^{||}}{m_p} \quad (4)$$

$$t \cong 2E_a \cdot m_p \left(\frac{E_i - \beta_a p_i^{||}}{m_p} \right) \cong S_{hN} \cdot n_c \quad (5)$$

The transverse energy spectrum of the secondary particles produced in *hA* and *AA* interactions at high energies may reflect the dynamics of the strong interaction process. This is connected with the fact that the transverse activities are mainly generated during the interaction process.

The effective temperature T of protons from reaction (1) as a function of the variable n_c is presented Fig.1. From this figure we see that the effective temperature T remained approximately constant on the level of $T = 50\ MeV$ in the interval $0.5 \leq n_c \leq 1.1$ and then increases. We note that there are no experimental points in $n_c < 0.4$ region. This is connected with our methodical difficulties to identify protons with momentum $p_p > 1\ GeV/c$ from energetic π^+-mesons.

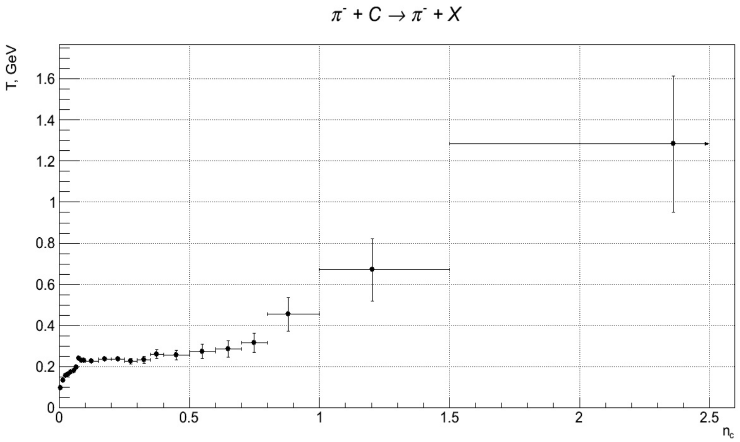

Figure 1: Dependence of the effective temperature T on the variable n_c for π^--mesons.

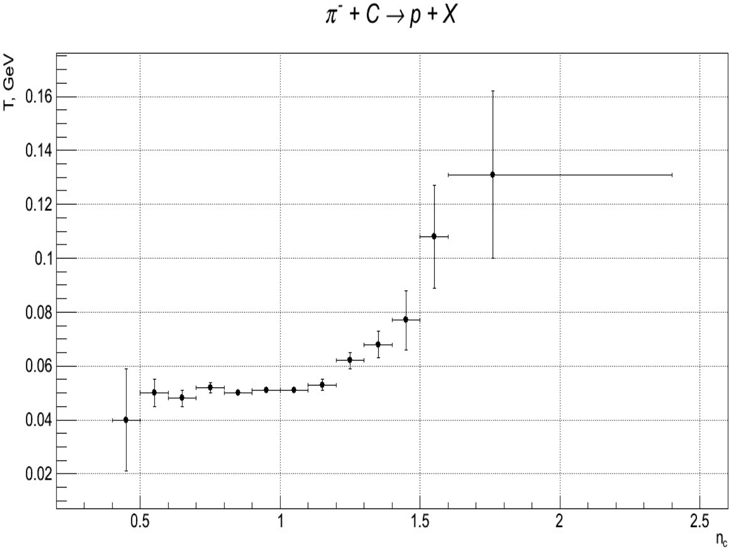

Figure 2: Dependence of the effective temperature T on the variable n_c for protons.

K_0 mesons analysis

The cumulative number distribution and the rapidity distribution of K^0-mesons from $\pi^- C$ interactions at 40 GeV/c are shown on Fig.5. We see that K^0-mesons are mainly produced at comparatively small values of n_c ($< n_c >= 0.2528$) and are produced in the central rapidity region ($< y_{lab} >= 2.197$).

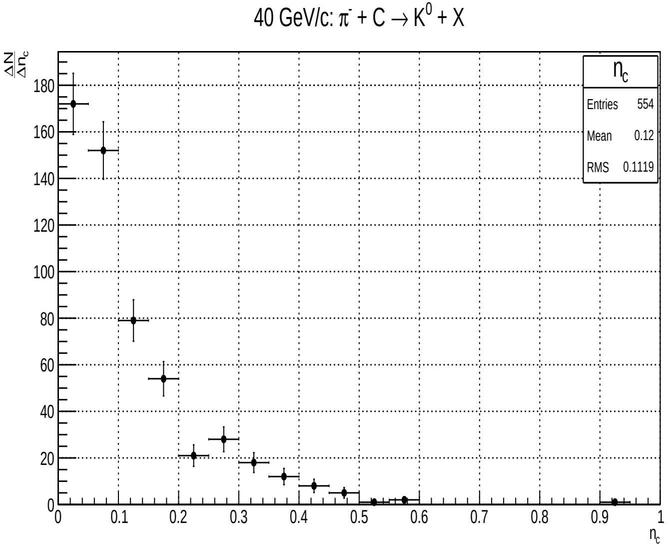

Figure 3: Cumulative number n_c distribution of K^0-mesons.

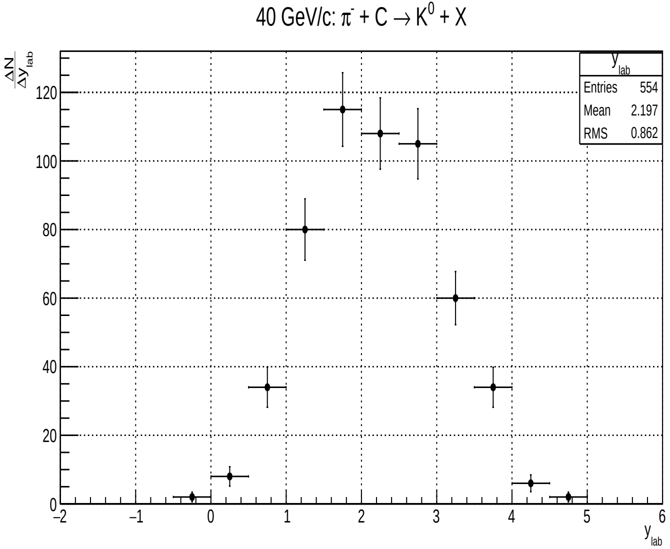

Figure 4: Rapidity distribution of K^0-mesons.

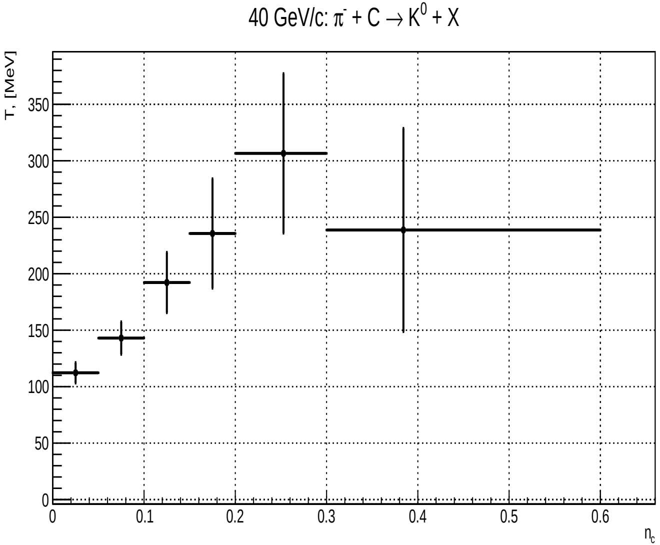

Figure 5: Dependence of the temperature T as a function of n_c.

In the first interval of the variable n_c which gives the beginning of the phase transition line with $T = T_c$, we calculated the value of the target mass m_c by the formula,

$$m_c^p = m_p \cdot < n_c^p > \simeq 0.938 GeV \cdot 0.52(\pm 0.001) = 0.487 GeV \approx \frac{m_p}{2}$$

where $< n_c^p >$ is the average value of n_c in the first n_c interval from which begins a plateua. Note that we obtained the value of the target mass close to the half mass of proton. The similar estimations for π^- and K_0 mesons give the next values:

$$m_c^{\pi^-} = m_p \cdot < n_c^{\pi} > \simeq 0.938 GeV \cdot 0.075(\pm 0.0006) = 0.070 GeV \approx \frac{m_{\pi^-}}{2}$$

$$m_c^{K_0} = m_p \cdot < n_c^{K_0} > \simeq 0.938 GeV \cdot 0.253(\pm 0.004) = 0.237 GeV \approx \frac{m_{K_0}}{2}$$

So, in the case of π^- and K_0 mesons we also obtained the values of the target mass m_c calculated in the first n_c interval which corresponds to the onset of the mixed phase close to half masses of the these particles. Fig.1 and Fig.2

Results of these calculations are presented on Fig.7. So, Fig.7 shows the dependence of the half mass of π^--mesons, K_0-mesons and protons as a function of the target mass m_c calculated at the condition $m_i/2 = m_c$.

We observe a linear dependence between the half mass of particles and the target mass calculated at the beginning point of the mixed phase, in other words, the dependence between above mentioned two masses on Fig.7 can be expressed by the following formula

$$\frac{m_i}{2} = \tan\alpha \cdot m_c \tag{6}$$

with $\tan\alpha = 1$.

On the basis of the experimental observations obtained in dependencies of the effective temperatures on the variable n_c of π^--mesons, K_0-mesons and protons from $\pi^- C$ interactions at 40 GeV/c we suggest that the mixed phase of the phase transition process begins from the point when the value of the mass which is required from the target equals to the about half mass of the considered secondary particle (see Fig.1 and Fig.2). This equilibrium state (or the mixed phase) is continued to the end of the phase transition line with approximately constant temperature $T = T_c$.

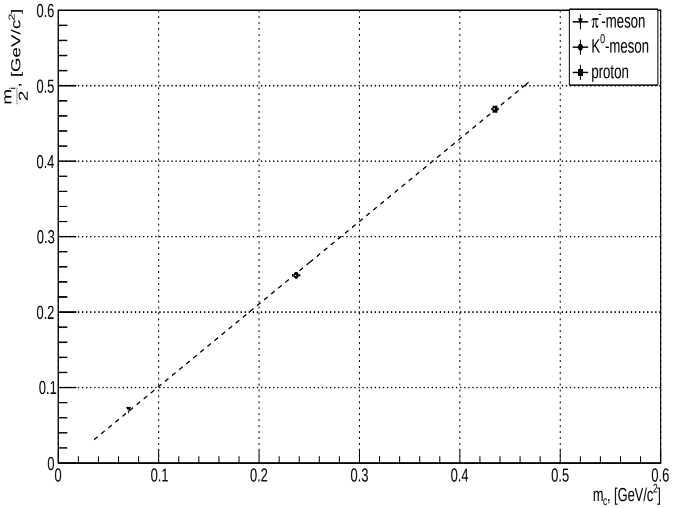

Figure 6: Dependence between $\frac{m_i}{2}$ and target mass $m_c = m_p \cdot < n_c >$ calculated at the condition $m_i/2 = m_c$.

Determination of the particle emission region size $r(n_c)$, volume $V(n_c)$ and energy density $\epsilon(n_c)$ at breaking points

$$m_c = m_p \cdot n_c = E - P_{||} \tag{7}$$

$$r = \frac{1}{m_p \sqrt{n_c}} = \frac{0.21[fm]}{\sqrt{n_c}} \tag{8}$$

$$V(n_c) = \frac{4\pi}{3} r^3 = \frac{4\pi}{3} \left(\frac{1}{\mu} \right)^3 \tag{9}$$

$$\epsilon(n_c) = \frac{\sqrt{2 E_a m_p n_c}}{V} \tag{10}$$

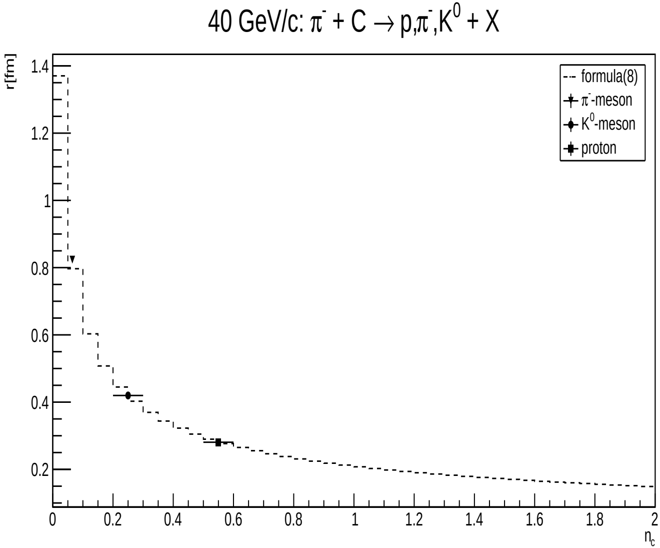

Figure 7: Dependence of the particle emission region size as a function of n_c.

	$< n_c >$	$r[fm]$	$V[fm^3]$	$\epsilon[GeV/fm^3]$
π^-	0.075 ± 0.0006	0.76 ± 0.006	1.88	1.25
K^0	0.237 ± 0.004	0.43 ± 0.007	0.33	12.5
p	0.52 ± 0.001	0.29 ± 0.001	0.103	60.38

Table 1:

From Table 1 we see that with increasing of the variable n_c values of parameter r and $V(n_c)$ decrease and energy densities increase essentially. In other words, the onset of the mixed phase of the deconfinement phase transition begins at large values of energy density in dependence on their rest masses.

Conclusion

On the basis of the experimental analysis of the parameter T as a function of the cumulative number n_c of π^--mesons, K_0-mesons and protons produced in $\pi^- C$ interactions at 40 GeV/c we suggest that the onset of the mixed phase of the phase transition process begins when the target mass value $m_c = m_p \cdot n_c$ equals to the half rest mass of particles $\frac{m_i}{2}$.

Frame Title

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Thank your for attention