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Half masses of particles produced in π^-C interactions at 40 GeV/c and phase transition

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Abstract. In this paper, we present the experimental analysis of the parameter T (temperature) as a function of the cumulative number n_c of π^- - mesons, K_0 - mesons and protons produced in π^- C interactions at 40 GeV/c. On the basis of this analysis, we determined a dependence between the half mass of the particle ($m_i/2$) and the target mass value ($m_c = m_p n_c$), which is required from the target for the production of the particle. We suggest that the dependence between the two masses mentioned above may be related to the beginning of the mixed phase with constant temperature.

1 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 strong interactions, 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. However, 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 following 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 that the signatures strengthen and then weaken again as the critical point is approached and then passed [2].

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- if the phase transition (i.e. a rapid change in the number of degrees of freedom) occurs, 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 a continuation of our previous publications [7–10].

2 Experimental method

The experimental material was obtained using the Dubna two meter propane (C_3H_8) bubble chamber exposed to π^- mesons with a momentum of 40 GeV/c from Serpukhov accelerator. All distributions in this paper were obtained under the condition of 4π geometry.

The average uncertainty of the momentum measurements is $\sim$ 12%, and the average uncertainty of the angular measurements is $\sim$ 0.6%.

All secondary negative particles are considered as π^- mesons. The average boundary momentum for which π^- mesons were well identified in the propane bubble chamber is $\sim$ 70 MeV/c. As regards the identification problem between energetic protons and π^+ mesons, protons with a momentum more than $\sim$ 1 GeV/c are included into π^+ mesons. The average boundary momentum for which protons are detected in this experiment is $\sim$ 150 MeV/c. Thus, secondary protons with momenta from $\sim$ 150 MeV/c to $\sim$ 1 GeV/c are used for proton distributions.

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

3 Effective temperature T as a function of a cumulative number n_c

In our previous papers [7–10], we studied dependencies of the temperature T on the variable n_c (or t) called the cumulative number. This variable in the fixed target experiment is determined by the following formula:

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

where P_a, P_b and P_i are four-dimensional momenta of the incident particle, target and secondary particles, correspondingly; E_i is the energy and $p_i^{\parallel}$ is the longitudinal momentum of secondary particles; $\beta_a = p_a/E_a$ is the velocity of an incident particle. At high energies $\beta_a \cong 1$ and m_p is a proton mass. From Eq. (4) we see that this variable is a relativistic invariant.

On the other hand, the variable n_c is related at high energies to the transferred momentum t by the following equation:

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

where $S_{hN} \simeq 2E_a m_p$ is a total energy squared for a hN interaction, which is constant in every experiment, so n_c is the main variable which determines the transferred momentum t.

For secondary particles produced in a region kinematically forbidden for hN interactions, $n_c > 1$. This fact gives us an opportunity to select particles in a given event of hA and AA interactions at high energies that are produced in a region which is not allowed for hN interaction. This is another reason why we use this variable.

The above mentioned advantages of the variable n_c such as relativistic invariance, the direct relation with the transferred momentum t (or p_T) and the identification of cumulative particles make it sensitive to the dynamics of the multiparticle production process in hA and AA interactions.

The transverse energy spectrum of secondary particles produced in hA and AA interactions at high energies may reflect the dynamics of the strong interaction process. It can be explained by the fact that the transverse processes are mainly generated during the interaction.

The effective temperature T of protons from reaction (1) as a function of the variable n_c is presented in Fig. 1. As can be seen from the figure, the effective temperature T remains approximately constant at the level of $T = 50$ MeV in the range $0.5 \leq n_c \leq 1.1$ and then increases. It should be noted that there are no experimental points in $n_c < 0.4$ region. The reason are methodical difficulties to identify protons with momentum $p_p > 1$ GeV/c from energetic π^+ mesons.

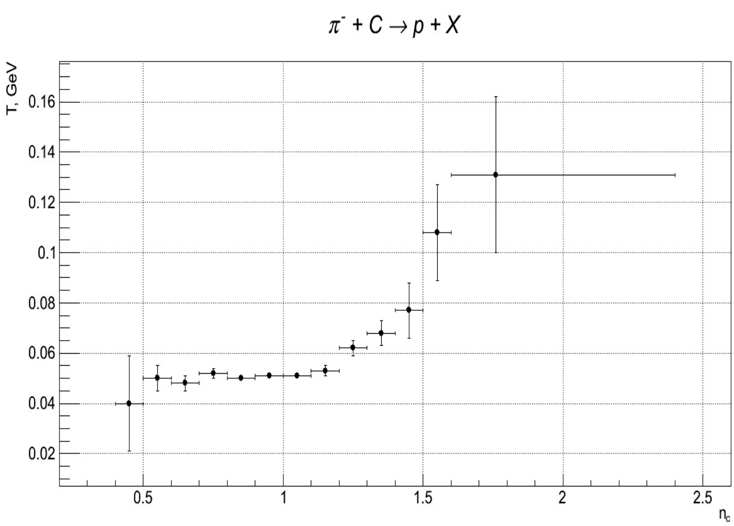

Figure 1. Effective temperature T vs cumulative number n_c for protons

3.1 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 in Figs. 3 and 4. As is seen, K^0 mesons are mainly

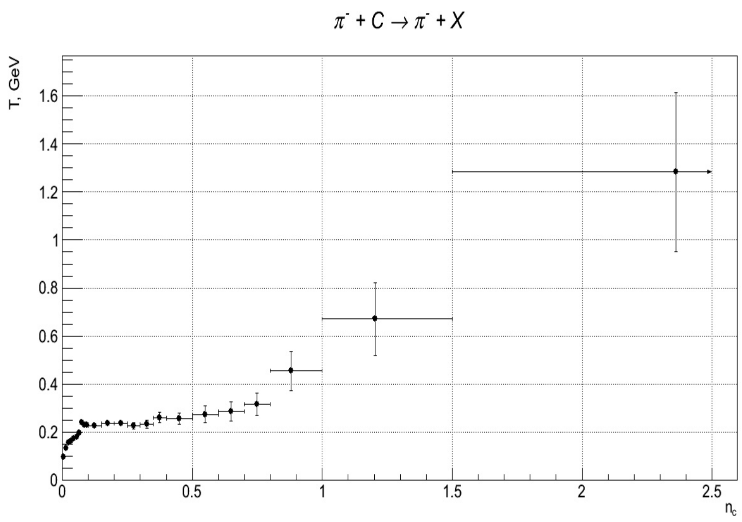

Figure 2. Effective temperature T vs cumulative number n_c for π^- mesons

produced at comparatively small values of n_c ($< n_c >= 0.2528$) and in the central rapidity region ($< y_{lab} >= 2.197$).

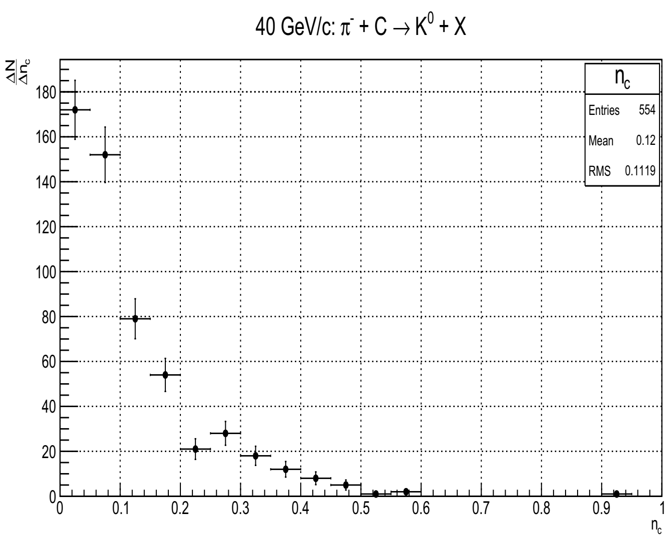

Figure 3. Cumulative number n_c distribution of K^0 mesons

The temperature T as a function of the n_c for K^0-mesons is presented in Fig. 5. As can be seen, with increasing of the variable n_c, the effective temperature T increases up to $n_c \simeq 0.2$ and then tends to be constant in the range $0.2 < n_c < 0.6$.

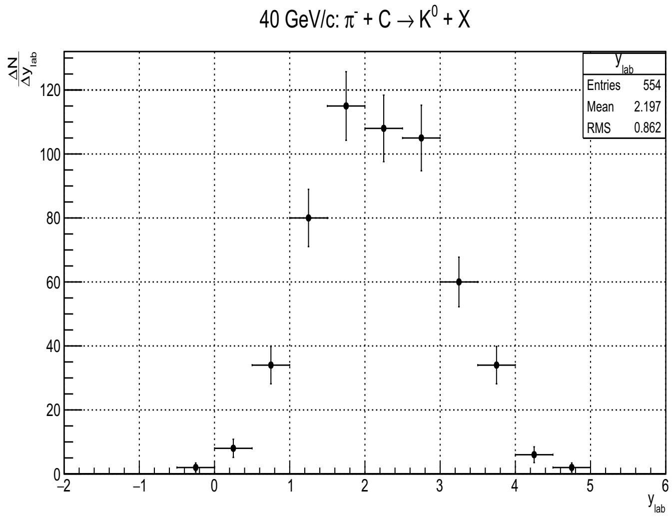

Figure 4. Rapidity distribution of K^0 mesons

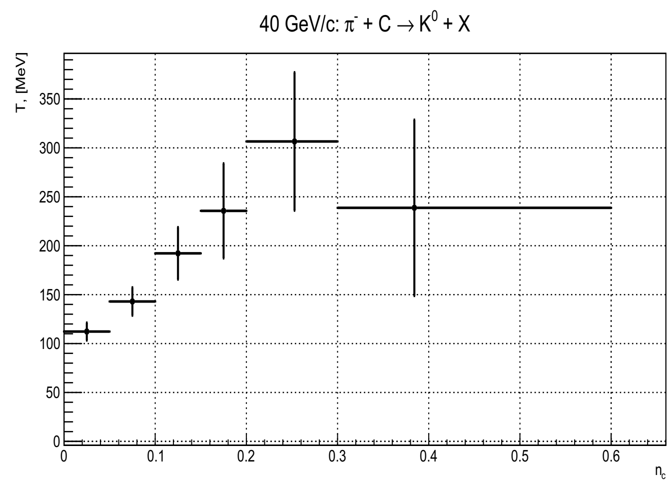

Figure 5. Temperature T as a function of n_c

In the range of 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 using the following relation:

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

where $< n_c^p >$ is an average of n_c in the n_c range where a plateau begins. Note that we obtained the target mass magnitude close to a half mass of proton. Similar estimations for π^- and K_0 mesons give the following magnitudes:

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

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

Thus, in case of π^- and K_0 mesons, we also calculated the target mass m_c in the n_c interval corresponding to the onset of the mixed phase close to half masses of these particles (Figs. 1, 2 and 5).

The results of these calculations are presented in Fig. 6. Fig. 6 shows 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 see that the obtained half mass of particles depends linearly on the target mass in the beginning of the mixed phase, in other words, the dependence between the two masses mentioned above (Fig. 6) can be described by the following relation:

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

with $\tan\alpha = 1$.

Using the obtained dependencies of the effective temperatures on n_c for 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 when the value of the mass which is required from the target is equal to approximately a half of the considered secondary particle mass (see Figs. 1, 2 and 5). This equilibrium state (or the mixed phase) continues to the end of the phase transition line with approximately constant temperature $T = T_c$.

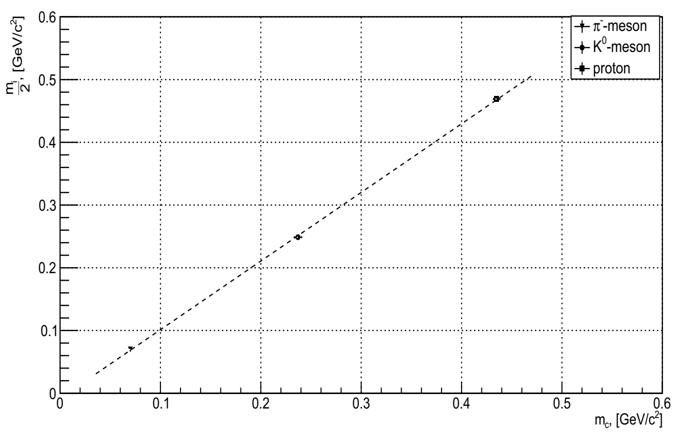

Figure 6. $\frac{m_i}{2}$ vs target mass $m_c = m_p \cdot < n_c >$ calculated under the condition that $m_i/2 = m_c$

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

In collisions of hadrons and nuclei at high energies, a system with invariant mass $\sqrt{s}$ with a large density fluctuation is produced as a result of interaction process. This system is expanded up to the hadronization temperature and then secondary particles are produced. Measuring angular and momentum characteristics of the secondary particles, one can determine the mass (m_c) of the target necessary to produce every secondary particle using (see Eq. 4)

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

The particle emission region size r is determined by the following equation [7]:

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

where m_p is the proton mass, $\frac{1}{m_p} = 0.21[\mathrm{fm}]$ is the Compton wavelength of the proton, n_c is the cumulative number. We note that the parameter r is determined by the Compton wavelength of the proton and the cumulative number n_c. This means that cumulative particles with $n_c > 1.0$ are produced at small values of the parameter r in comparison with noncumulative particles with $n_c < 1.0$.

Using Eq. (8), we calculated the values of the parameters r under the condition that $\frac{m_i}{2} = m_c \cdot < n_c >$, which corresponds to the onset of the mixed phase for π^- mesons, K_0 mesons and protons. Results of these calculations are presented in Fig. 7.

Using the obtained results, we can calculate the effective volume occupied by the particles produced in the n_c interval which corresponds to the beginning of the mixed phase. For simplicity, the volume was presented as a sphere:

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

where $\mu = m_p\sqrt{n_c}$ is the target mass value, which determines parameter r.

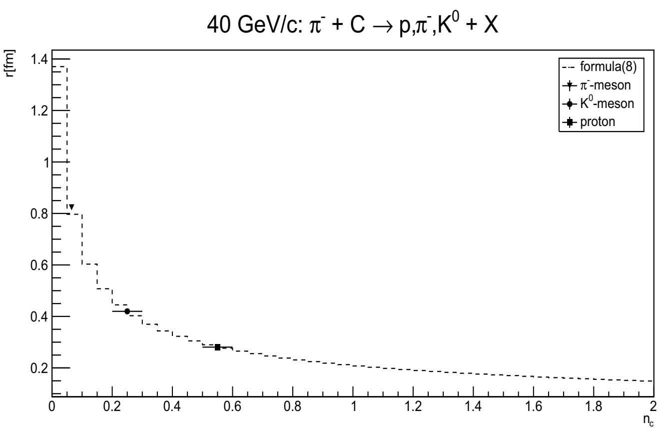

Figure 7. Particle emission region size as a function of n_c

Now we can estimate the energy density $\epsilon(n_c)$ at the beginning points of the mixed phase using Eq. (10) [10]:

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

Values of r parameters, volume $V(n_c)$ and energy densities $\epsilon(n_c)$ calculated by formulae (8)-(10) at $\frac{m_i}{2} = m_p \cdot < n_c >$ for π^- mesons, K_0 mesons and protons from $\pi^- C$ interactions at 40 GeV/c are shown in table.

	$< n_c >$	r[fm]	V[fm^3]	ϵ[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

From table, we see that when n_c increases, the parameters r and $V(n_c)$ decrease and the 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 depending on their rest masses.

Conclusion

Using 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 conclude that the onset of the mixed phase of the phase transition process begins when the target mass value $m_c = m_p \cdot n_c$ is equal to a half of the rest mass of particles $\frac{m_i}{2}$.

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