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THE TEMPERATURES OF NEGATIVE PIONS IN LIGHT IONS COLLISIONS WITH CARBON AND TANTALUM NUCLEI AT 4.2·A GeV/c

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INTRODUCTION

The temperature and density of nuclear matter are among the main parameters of equation of state determining the phase transition mechanism. To obtain the temperature of secondary hadrons in the experiment one usually estimates the value of the inclusive spectrum slope. Generally, different criteria to select samples of secondaries for analysis have been used. So, in paper [1] the particles emitted at 90° in the center -of- mass system (CMS) of Ne + NaF interactions at 2.1 GeV/nucleon were investigated and the value of negative pion temperature $E_o = 102$ MeV was obtained; later at the same experimental conditions for Ar + KCl at 1.8 GeV/nucleon [2] the apparent temperature of 58 MeV was determined for 95% of the pion total yield and 110 MeV for the remaining 5%. On the other hand the kinematically forbidden region was studied in paper [3] and the temperature of 50 MeV has been obtained [4] for negative pions produced at 180° in the collisions of deutrons with different nuclei at 3.36 GeV/nucleon. As it could be expected such kind of restrictions allows to obtain actual information about the initial stage of the multiparticle production process (the extremely compressed matter) and to separate different mechanism contributions. In addition, the transverse motion in nuclear collisions is an effective probe [5] to test the validity of theoretical models. The analysis must be performed for different kinds of secondaries and selection criteria used at the equal experimental conditions.

The detailed analysis of the transverse negative pion spectra and determination of pion temperatures is the main goal of the work. We have investigated the dependence of temperature on π^- mesons rapidity and on "centrality" of the interactions.

We have used the approximation of the transverse momentum invariant spectra of secondaries obtained in the statistical bootstrap model in papers [6,7] in order to obtain the temperature values :

$$\frac{1}{2\pi p_\perp}\frac{d(dN/dy)}{dp_\perp} \sim \sqrt{p_\perp^2+m^2}\sum_{n=1}^{\infty} K_1\left[n\frac{\sqrt{p_\perp^2+m^2}}{T}\right], \qquad (1)$$

where T is the temperature, $m = m_\pi$ for pions and K_1- modified Bessel functions (Macdonald functions). One can also determine the temperature based on the average value of transverse momentum of secondary hadrons as it was done in paper [6] .

SOME FEATURES OF THE QUARK-GLUON STRING MODEL

In previous papers [8] a good agreement of the Dubna cascade model calculations (DCM) [9] with experimental data on inclusive characteristics and correlations of secondaries was shown. In this work we have used the next generation of DCM - the quark-gluon string model (QGSM) [10].

In papers [10,11] the model is presented in details. To describe the evolution of the hadron and quark-gluon phases a coupled system of Boltzmann-like kinetic equations has been used in the model. The nuclear collision is treated as a mixture of independent interactions of the projectile and target nucleons, stable hadrons and short-living resonances. A resonant $\pi + N \to \Delta$ reactions and pions absorbtion by NN- quasi-deuteron pairs as well as $\pi + \pi \to \rho$ reactions are taken into account. The formation time of hadrons is also included in the model. The quark-gluon string model [10] has been extrapolated to the range of intermediate energy ($\sqrt{s} \leq 4$ GeV) to use it as a basic process during the generation of hadron-hadron collisions.

The included processes are illustrated in Fig.1 for the case of NN interactions. Similar processes are accessible also for πN collisions as well as the additional reaction (1f) corresponding to planar quark diagram. A binary process (1a) gives the main contribution which is proportional to $1/p_{lab}$. It

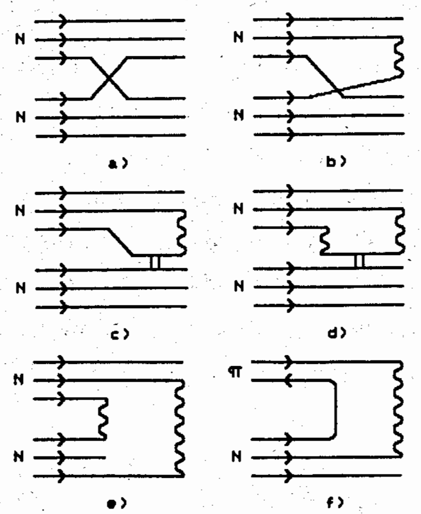


Fig.1 *Topological quark diagrams for main processes accounted in the model at $\sqrt{s} \leq 4$ GeV: a - binary, b - "undeveloped" cylindrical, c - and d - diffractive, e - cylindrical, f - planar. Solid lines mark quarks and the wave ones show strings.*

corresponds to quark rearrangement without direct particle emission in the string decay. This reaction predominantly results in production of resonances (for instance, $p+p \to n+\Delta^{++}$) which are the main source of pions.The angular dependence for reaction (1a) can be parameterized as $d\sigma/dt \cong \exp(-bt)$, where $b(s) = 2.5+0.7\cdot\ln(s/2)$

and t is the four-momentum transfer. The comparable contributions to inelastic cross section decreasing with p_{lab} growing come from diagrams corresponding to the "undeveloped" cylindrical diagrams (1b) and from the diffractive (1c,d) processes. The pion transverse momenta produced in quark-gluon string fragmentation processes in the mentioned reactions are the product of two factors. These factors are: a string motion in the whole as a result of transverse motion of constituent quarks and $q\bar{q}$ production in string breakup. Transverse motion of quarks inside hadrons was described by Gaussian distribution with variance $\sigma^2 \cong 0.3(\mathrm{GeV}/c)^2$ The transverse momenta k_T of produced $q\bar{q}$ pairs in CMS of the string follows the next dependence: $W(k_T) = 3b/\pi(1 + bk_T^2)^4$.

The cross sections of hadron interactions were taken from the experiments. Isotopic invariance and predictions of additive quark model [12] (for the meson-meson cross sections etc.) were used to avoid the data deficiency. The resonance interaction cross sections were taken equal to the interaction cross sections of the stable particle with the same quark content. Also a real width of resonances was used.

This model was simplified in some aspects to increase the rate of nucleus-nucleus generation. In particular, coupling of nucleons inside the nucleus was neglected, the decay of the excited recoiled nuclear fragments and coalescence of nucleons were not involved either. So, 15.000 for each of (d,α,C)+C, 6.000 dTa and 3.000 CTa inelastic interactions were generated using QGSM. Comparison with the model allows one to distinguish the kinematically caused effects and permits to interpret the results more definitely.

EXPERIMENTAL RESULTS

In the paper we study the transverse momentum invariant spectra of π^- mesons, produced in the inelastic dC, αC, CC, dTa, αTa and CTa interactions at 4.2 GeV/c per nucleon. The experimental data have been obtained using a 2-m propane bubble chamber exposed to beams of nuclei at the Dubna synchrophasotron. Three 1 mm thick tantalum plates were mounted inside the chamber. General characteristics of the interactions and specific methods of data processing were published earlier in papers [8] . Practically all the secondaries emitted in 4π total solid angle have been detected in the chamber. The average minimal momentum for pion registration was about 70 MeV/c. The statistics of the experimental samples is presented in Table 1.

TABLE 1. Statistics of inelastic nuclear interactions.

Projectile nuclei	d	α	C
Number of events (C-target)	6684	4849	6806
(Ta-target)	1475	1149	1989

Collisions of Light Ions with Carbon Nuclei

The transverse momentum invariant spectrum of negative pions produced in the inelastic CC interactions is shown in Fig.2. The usage of approximation (1) gives the values of parameter $T_1 = (68 \pm 4)$ MeV for 60% of the total pion yield and $T_2 = (131 \pm 9)$ MeV for the remaining 40%.

When we obtained $p_\perp$ spectra at different rapidity intervals for the carbon target only one slope was observed.

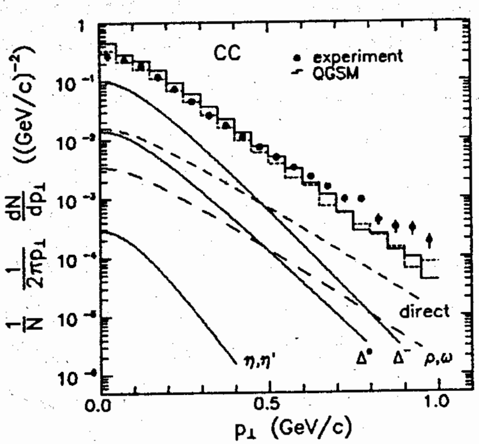
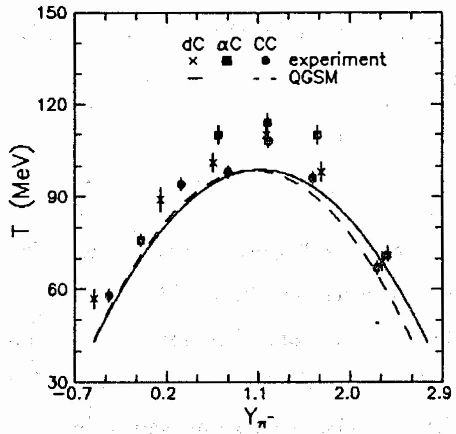


Fig.2 *The invariant spectrum of negative pions transverse momentum in the inelastic CC interactions. The histograms show results of the model (the dashed one includes the account of momentum resolution). Lines on the figure reproduce the spectra of different pion sources in QGSM.*

Fig.3 shows the dependence of negative pion temperature on the value of pion rapidity $y_\pi = 0.5 \cdot \ln(E + p_\parallel / E - p_\parallel)$. Experimental points are presented for inelastic dC, αC and CC collisions. The lines reproduce the model calculations for dC and CC interactions. The rapidity interval ranging was made due to the statistical considerations. It is seen from Fig.3 that the dependence has a wide maximum at the range of rapidity corresponding to CMS of nucleon-nucleon interaction ($y \cong 1.1$). Temperatures for different projectile nuclei are sufficiently close at the same rapidity intervals. It means that there is no pronounced A-dependence of T parameter. In the fragmentation region of colliding nuclei the magnitude of T is about 60 MeV and

it increases to 110 MeV in the central region. QGSM reproduces data quite satisfactorily in the fragmentation region but in the central region the experimental values of temperature exceed those of the model for about (10-15)%.



Thus, the observations qualitatively agree with the ideas based on the creation of a "hot" pion source whose highest degree of compression (in central region) results in high values of temperature.

Fig.3 *Negative pion temperature dependence on the pion rapidity in dC, αC and CC inelastic collisions. The lines reproduce the model calculations.*

The information about the origin of secondary particles generated in QGSM can help one to understand the observed dependence. As we have mentioned above, the dominant sources of pions in QGSM at our energies are decays of Δ and other resonances ($\rho, \omega, \eta, \eta'$) as well as "direct" reactions. We have marked as "direct" a sample of pions not produced in the resonance decays. For a nucleon-nucleon reaction at 4.2 GeV/c the relative pion intensities (contributions to the π^- multiplicity) in QGSM are:

$$\begin{array}{cccccccc} I_{\Delta^-} : & I_{dir} : & I_{\Delta^\circ} : & I_{\rho^\circ} : & I_{\rho^-} : & I_\omega : & I_\eta : & I_{\eta'} \\ 0.35 : & 0.43 : & 0.12 : & 0.03 : & 0.02 : & 0.02 : & 0.02 : & 0.01 \end{array} \qquad (2)$$

A solid histogram in Fig.2 represents QGSM calculations for the invariant transverse momentum spectrum of negative pions produced in the inelastic CC interactions. The dashed one shows the result of correction of the pion momentum values due to experimental uncertainties $\Delta p/p \cong (5-10)\%$. The account of experimental resolution improves the agreement with the data for small values of $p_\perp$ and is negligible for high values of transverse momentum. In paper [13] two different approaches were applied to the analysis of the pion transverse spectra from ultrarelativistic collisions of ions. Decays of resonances were also treated as the main source of pions. Both: the chemical equilibrium model and the statistical string fragmentation model of the initial hadronic abundances describe quite well the data only for $p_\perp > 0.2$ GeV/c but not for small $p_\perp$.

The lines in Fig.2 reproduce smoothing spectra of the mentioned sources in the QGSM for CC inelastic collisions. We obtain in the model the following relative intensities of the sources :

$$\begin{array}{cccccccccccccccc} I_{\Delta^-} & : & I_{dir} & : & I_{\Delta^\circ} & : & I_{\rho^\circ} & : & I_{\rho^-} & : & I_{\omega} & : & I_{\eta} & : & I_{\eta'} \\ 0.43 & : & 0.26 & : & 0.17 & : & 0.06 & : & 0.04 & : & 0.02 & : & 0.01 & : & 0.01 \end{array} \quad (3)$$

Within ~ (10-20)% the ratio (3) remains constant for different pion rapidities. The influence of secondary processes going from NN reactions (2) to CC interactions results in changing a relative contribution of direct reactions. The ratio of the pion yields is $I_{\Delta^-} : I_{dir} = 1.1 : 1$ for NN reactions (2) and $2.3 : 1$ for CC interactions. For tantalum target this ratio is growing up to $3.1 : 1$. The calculations shown in Fig.2 demonstrate also different slopes of the spectra. Using approximation (1) we have obtained the values of negative pion temperature for each source presented in Table 2. The magnitude of T changes in the range from 50 till 110 MeV similar to those in the experiment for different pion rapidity (see Fig.3).

TABLE 2. Pion temperature from different sources in QGSM.*

(CC inelastic collisions)

Source	Δ^-	direct reactions	Δ°	$\rho^-, \rho^\circ, \omega$	η, η'
Temperature(MeV)	68	110	73	106	50

Fig.4 shows rapidity dependence of pion temperatures obtained in the model for two dominant sources $-\Delta^-$ decays and direct reactions. The pion temperature in delta decays is systematically smaller than those in the direct reactions, probably, due to different phase space available for delta decays and direct reactions. In general, the temperature behaviour obtained in the model for different sources replicates those observed in the experiment.

*Typical errors of the parameter T obtained in the model have not exceed a few MeV and were not mentioned in the text.

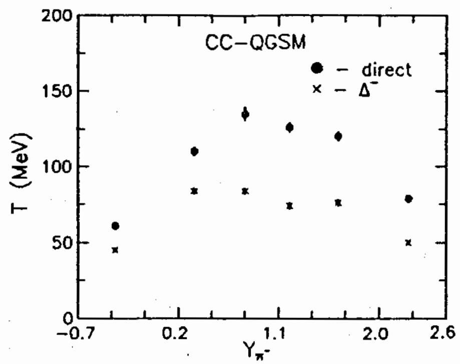


Fig.4 *Temperature dependence on rapidity of negative pions from Δ^- decays and direct reactions in CC inelastic collisions (QGSM calculations).*

Fig.5 presents relative contributions of the sources (normalized to unit) to different intervals of transverse momenta obtained in QGSM for CC inelastic interactions. For high values of $p_\perp$ the relative contribution of delta decays decreases. At the same time the influence of direct

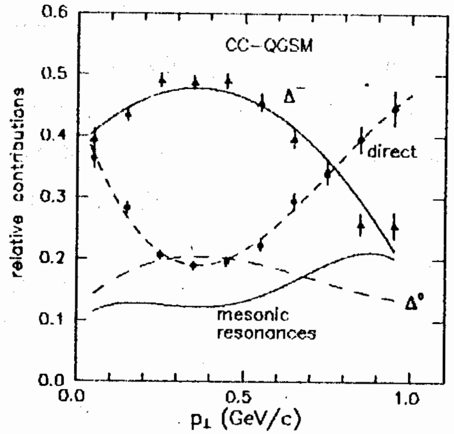


Fig.5 *Dependence of the relative contributions from different sources to pion multiplicity in QGSM on the value of pion transverse momentum for CC inelastic collisions. Polynomial approximations were used for the spectra smoothing.*

production mechanism becomes significant while $p_\perp$ growing.

Analyzing in detail the characteristics of different pion sources in QGSM, we have obtained the pion temperatures for two groups of pions emitted in the direct reactions:

- for pions produced in primary and secondary NN collisions (e.g. $NN \rightarrow NN\pi$);
- for π^- mesons emitted in the interactions of secondary pions and resonances (e.g. $\rho N \rightarrow N\pi$).

The yields of pions in these groups of reactions are related as 1.4:1.0. The pion temperatures for the two samples are $T = 107$ MeV and $T = 119$ MeV, respectively. About 10% of directly emitted pions were later scattered elastically. This results in temperature increasing to 140 MeV and 153 MeV, respectively.

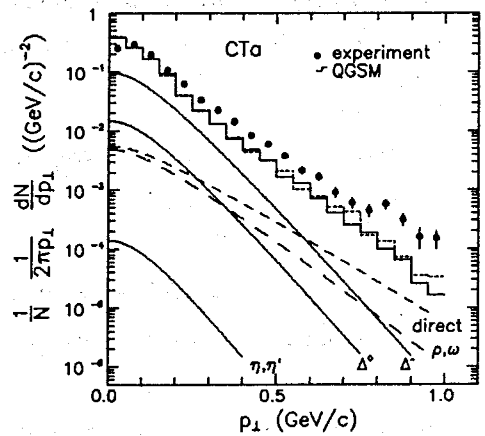
A similar temperature dependence has been also observed for pions emitted in the decays of delta resonances. So, approximately 20% of pions from Δ° were scattered elastically. The temperature value for this sample of pions is $T = 84$ MeV and for non-interacting pions $T = 69$ MeV.

A satisfactory agreement of the quark-gluon string model calculations for pion temperatures proves the assumption that the values of temperature observed in the experiment reproduce a complex superposition of different source slopes.

Interactions with Tantalum Nuclei

Transverse momentum invariant spectrum of negative pions produced in the inelastic CTa interactions is presented in Fig.6. Generally, the model reproduces the inclusive spectrum observed in the experiment. The varieties of pion momenta according to the experimental resolution do not change significantly the $p_\perp$ spectrum calculated in the model. There is some excess of high $p_\perp$ pions in the experiment similar to light nuclei collisions. The usage of approximation (1) gives the values of parameter $T_1 = (49 \pm 2)$ MeV for 49% of the total pion yield and $T_2 = (113 \pm 5)$ MeV for the remaining 51%.

The total transverse momentum spectra for CTa inelastic collisions and those spectra in different rapidity intervals show a bend at $p_\perp \cong 0.5$ GeV/c.



This important feature of spectra distinguishes CTa interactions from collisions of light nuclei and displays the appearance of one more slope of spectra corresponding to the high value of temperature. No satisfactory approximation

Fig.6 *The invariant spectrum of negative pion transverse momentum in CTa inelastic interactions. Notation is the same as in Fig.2.*

was found using only one T parameter. A good agreement with the experimental data was obtained for two parameters T_1 and T_2. Usually one interprets it as manifestation of two sources of pions with different temperatures. In paper [14] a "two - temperature" shape of transverse momentum invariant spectrum was explained due to different contributions of deltas produced at early and late stages of heavy ion

reactions. In paper [15] this effect was qualitatively explained taking into account the finiteness of the number of particles in the statistical ensemble and the resonant absorbtion mechanisms.

Fig.7 shows the behaviour of temperatures in the available region of rapidity for negative pions emitted in the inelastic dTa, αTa and CTa collisions. The lines correspond to QGSM calculations. The model agrees with the data. Only one slope

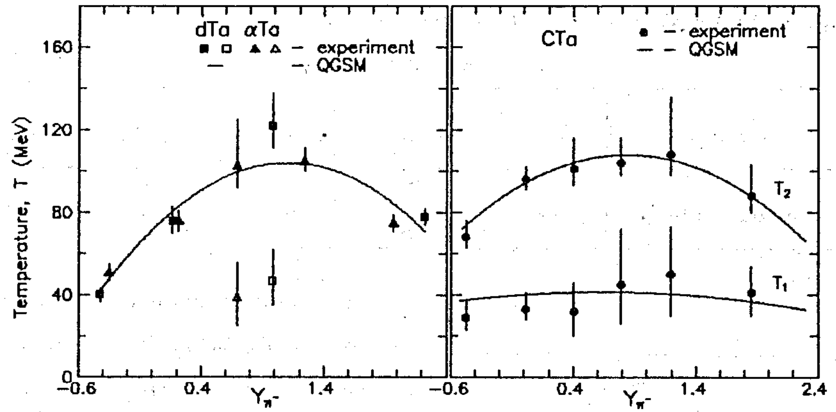


Fig.7 *Negative pion temperature dependences in the inelastic dTa, αTa and CTa interactions. The lines correspond to QGSM calculations.*

in spectra of π^- mesons from dTa and αTa interactions is seen both - in experiment and in the model. In the central rapidity region in dTa and αTa collisions the additional slope reveals but the contributions to corresponding invariant spectra are not remarkable. In CTa inelastic interactions two slopes are seen in the whole rapidity region. The value of temperature T_1 remains almost constant ($\cong 40$ MeV) for different rapidities and coincides with T_2 parameter for dTa and αTa collisions in the central region. The behaviour of temperature of the additional "hot source" is similar to that observed in the light nuclei interactions. The temperature values for different projectile nuclei do not significantly distinguish from each other at the same rapidity intervals.

The contribution ratio of the sources in QGSM for CTa inelastic collision is approximately the same as for CC interactions:

$$
\begin{matrix} I_{\Delta^-} & : & I_{dir} & : & I_{\Delta^\circ} & : & I_{\rho^\circ} & : & I_{\rho^-} & : & I_\omega & : & I_\eta & : & I_{\eta'} \\ 0.45 & : & 0.20 & : & 0.17 & : & 0.08 & : & 0.07 & : & 0.01 & : & 0.01 & : & 0.01 \end{matrix} \qquad (4)
$$

Ratio (4) is almost constant in different ranges of pion rapidity. Table 3 presents corresponding values of temperature. They have not changed significantly in comparison with CC collisions.

TABLE 3. Pion temperature from different sources in QGSM.

(CTa inelastic collisions)

Source	Δ^-	direct reactions	Δ°	$\rho^-, \rho^\circ, \omega$	η, η'
Temperature(MeV)	66	28 128	64	95	57

The same conclusion is also valid for relative contributions of the sources to $p_\perp$ spectrum which is shown in Fig.8. The influence of the direct production mechanism increases also with $p_\perp$ while the relative contribution of delta decreasing.

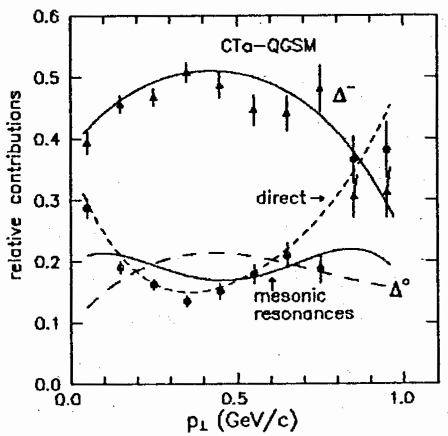


Fig.8 Dependence of the relative contributions to pion multiplicity from different sources in QGSM on the value of pion transverse momentum for CTa collisions. Notation is the same as in Fig.5.

Fig.9 presents temperature dependence obtained in QGSM on rapidity for pions produced in the direct reactions and Δ^- decays. For every rapidity interval the shapes of the invariant spectra are considerably different. In comparison with the decay mechanism the spectra of the directly produced pions obviously show two slopes. And corresponding temperatures T_1 and T_2 remain almost constant within their error bars.

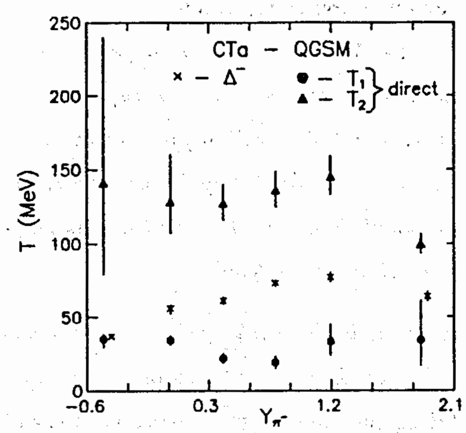


Fig.9 Temperature dependence on rapidity of negative pions from Δ^- decays and direct reactions in CTa inelastic collisions (QGSM calculations).

The direct reactions were classified into two groups for CTa collisions in the same manner as for CC interactions. But in this case we observe quite another ratio of pion yields in the groups. The number of π^- mesons emitted in the interactions of secondary pions and resonances with nucleons in QGSM is almost four times greater than that in primary and secondary NN reactions. For both groups of pions we have observed the "two-temperature" shape of transverse momentum spectra. The corresponding values of temperatures and relative contributions to the total pion yield are $T_1 = 26$ MeV (22%), $T_2 = 128$ MeV (78%) for the first group of pions (from NN-reactions) and $T_1 = 28$ MeV (53%), $T_2 = 129$ MeV (47%)- for the second one. So, the additional slope (T_2) in direct reactions is mainly related to the interactions of secondary pions and resonances with nucleons.

The temperature behaviour for pions produced in delta decays in the generated CTa collisions is similar to the generated CC interactions. In CTa inelastic collisions about one third of negative pions produced in Δ° decay was scattered elastically. This results in temperature increasing from 61 MeV up to 68 MeV. The model allows one to reconstruct kinematical characteristics of the parent deltas using momenta of daughter pions and protons (neutrons). So, one can obtain the transverse momenta invariant spectrum of Δ resonances and the corresponding value of delta temperature: $T_{\Delta^-} \cong 120$ MeV. Basing on the results shown in Fig.9 we can also get pion temperature dependence on the mass of parent resonance. The results for π^- mesons from Δ^- decays in QGSM presented in Fig.10 agree with the calculations of paper [16] .

Thus, the main features of transverse momentum invariant spectra of negative pions produced in light relativistic nuclei collisions both with the carbon and tantalum nuclei can be described in framework of the quark-gluon string model.

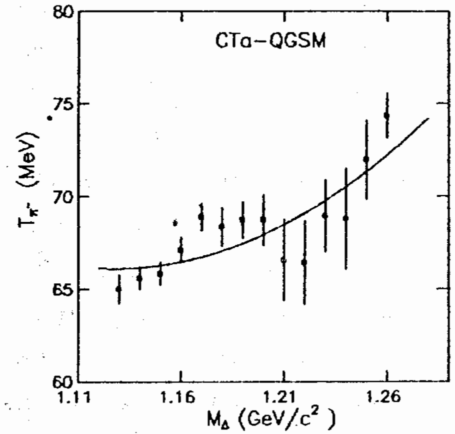


Fig.10 *Temperature dependence of negative pion from Δ^- decays on the mass of delta in QGSM for CTa inelastic interactions. Closed cycles are the result of calculations and the solid line is polynomial approximation.*

In comparison with the carbon nucleus the contribution of intranuclear rescattering mechanism in the interactions of the projectile nuclei with the tantalum target becomes significant. It changes the shape of $p_\perp$-spectra and comes in particular to appearance of the additional slope in the transverse momentum spectra of the pions. It follows that the obtained "temperatures" characterize the slope values of the invariant spectra and that they reflect the observed dynamical features of the multiparticle production mechanism.

Influence of Selection Criteria

Non-trivial properties of nuclear matter can be observed as it is expected at extremely high densities which are accessible in heavy ion central collisions. In papers [17-19] it is shown that net charge of secondary particles Q is an effective probe of collision "centrality". In the experiment we have analyzed the transverse momentum invariant spectra of pions produced in the inelastic nuclear interactions with different values of Q and obtained the following results: in the (d, α)+(C,Ta) only one slope is seen with $T = (80 \div 90)$ MeV and in CTa collisions - two slopes with $T_1 = (60 \div 70)$ MeV and $T_2 = (120 \div 150)$ MeV. No systematical dependence of temperature values on the impact parameter has been found. This confirms the conclusion of paper [20] about weak dependence of the momentum, angular and rapidity distributions of pions on the centrality of light ion collisions.

The invariant spectra of pions emitted at the angles $90° \pm 10°$ in center-of-mass system of CC and CTa inelastic collisions have been also analysed. For the equal mass CC interactions the center-of-mass system is CMS of nucleon - nucleon collisions. For

unequal mass (asymmetrical) CTa interactions we have used CMS of participating protons. The results are presented in Table 4. The invariant spectra of pions in CTa collisions show only one slope. The obtained values of pion temperatures coincide

TABLE 4. Temperatures of π^--mesons, emitted at the angles $90° \pm 10°$ in CMS of CC and CTa interactions.

Interactions	CC	CTa
Experiment	118 ± 3	102 ± 4
QGSM	103 ± 2	82 ± 3

with those observed and calculated in the central rapidity region. The experimental values of temperature exceed the temperatures in QGSM for about (15÷20) MeV. The magnitudes of parameter T do not significantly depend on the selected angular restriction limits. The marked disagreement takes place due to the excess of high $p_\perp$ pions observed in the experiment.

CONCLUSIONS

The slope parameters of transverse momentum invariant spectra of negative pions produced in the inelastic (d,α,C)+(C,Ta) interactions at 4.2 GeV/c per nucleon have been analyzed and the values of corresponding temperatures have been obtained. For the carbon target in the fragmentation region of colliding nuclei the temperature is close to 60 MeV and grows up in the central rapidity region till 110 MeV. In CTa collisions the "two-temperature" shape of the spectrum is observed; the contribution of the "hot source" increases in the central region and is weakly seen in dTa and αTa interactions.

The obtained values of temperature for pions emitted at $90° \pm 10°$ in CMS of CC and CTa interactions are close to those parameters observed in the central rapidity region of projectile nuclei interactions with the carbon target.

The pion temperatures do not remarkably depend on the centrality of collisions. No significant dependence of temperature on the atomic weight of both, projectile and target nuclei has been found .

The experimental results are compared in details with the calculations performed in framework of the quark-gluon string model. The model reproduces data quite satisfactory, except the central rapidity region where some excess of high $p_\perp$ pions is observed.

Comparisons with the model show that the pion temperatures in all investigated inelastic nuclear collisions are determined by superposition of partial contributions of different sources (decays of resonances, direct reactions). Both: the pion temperature rise in central rapidity region and the appearance of the additional slope in the transverse momentum pion spectra in CTa interactions are caused, especially, due to intranuclear rescattering mechanism of mesons and resonances with direct π^- meson production.

Perhaps, investigations devoted to the analysis of another hadron spectra and comparison of the results with calculations of "non-cascade" models would be fruitful.

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