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THE BOLTZMANN TEMPERATURE OF NEGATIVE PIONS IN INELASTIC (d, α, C)+(C, Ta) COLLISIONS AT 4.2 A GeV/c

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The slopes of the noninvariant center-of-mass energy spectrum of negative pions in inelastic collisions of nuclei d, α, C with C and Ta targets at 4.2 A GeV/c are studied. The temperatures of the negative pions are obtained using the Boltzmann approximation of the spectra. The two-temperature shape of c.m. energy spectra is observed. The values of temperature do not depend significantly both on collision «centrality» and on atomic weight of the projectile nuclei.

The experimental results are compared with the calculations in the framework of the quark-gluon string model. The influence of resonances and directly produced pions on temperature values is studied.

The investigation has been performed at the Laboratory of High Energies, JINR.

Больцмановская температура отрицательных пионов в неупругих (d, α, C)+(C, Ta)-соударениях при 4,2 А ГэВ/с

С.Бацкович и др.

Изучены наклоны неинвариантных энергетических спектров отрицательных пионов в системе масс сталкивающихся ядер в неупругих взаимодействиях (d, α, C) с ядрами (C,Ta) при 4,2 А ГэВ/с. С помощью больцмановской аппроксимации спектров получены величины температур отрицательных пионов. Изученные спектры имеют два наклона. Величины температур не зависят заметно ни от «центральности» соударения, ни от атомного веса снаряда. Экспериментальные результаты сравниваются с вычислениями по модели кварк-глюонных струн. Изучено влияние резонансов и прямо рожденных пионов на величины температур.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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I. Introduction

The temperature and density of nuclear matter are among the main parameters of an equation of state determining the phase transition mechanism. To obtain the temperature of secondary hadrons in the experiment, one usually estimates the inclusive spectrum slope. So, in paper/1/ the inverse slope of the energy spectrum of negative pions emitted at 90° in the center-of-mass system (CMS) of Ne + NaF interactions at 2.1 GeV/nucleon was used to estimate the fireball temperature in the framework of a simple thermodynamic performance. Later/2/ for an analogous selection criterium of pions in Ar + KCl at 1.8 GeV/nucleon an apparent temperature of 58 MeV was determined for 95% of the pion total yield and 110 MeV for the remaining 5%.

In this paper we present the temperature values of negative pions obtained for interactions of light d, α and C nuclei with carbon and tantalum at an incident momentum of 4.2 GeV/c per nucleon. A detailed comparison with the calculations based on the mixture of independent hadron collisions (quark-gluon string model, QGSM) has been also made.

II. Experimental Data

The experimental data have been obtained using a 2-m propane bubble chamber placed in a magnetic field of 1.5 T and exposed to beams of light relativistic nuclei at the Dubna synchrophasotron. Three 1 mm thick tantalum plates were mounted inside the chamber. The general characteristics of the interactions and specific methods of data processing were published earlier in papers/3/. Practically all the secondaries emitted at a 4π total solid angle were detected in the chamber. When scanning, all negative particles, except identified electrons, were considered as π^- mesons. The contaminations by misidentified electrons and negative strange particles do not exceed 5% and 1%, respectively. The average minimum momentum for pion

Table I. Statistics of inelastic nuclear collisions

Target	C			Ta		
Projectile	d	α	C	d	α	C
N_{events}	6684	4849	6806	1475	1149	1989

registration is about 70 MeV/c, and the mean error in measuring the π^- meson momentum is $\langle \Delta p/p \rangle \cong 6\%$. The statistics of the observed nuclear interactions is presented in Table I.

III. Temperatures of Negative Pions

To estimate the temperature of negative pions, we have used the predictions of thermodynamic models/4/. In particular, the energy spectrum of negative pions in the CMS of colliding nuclei can be presented using the temperature T of a Maxwell — Boltzmann gas:

$$\frac{d^2N}{dE^* d\Omega} = \mathrm{const}\cdot p^* \cdot E^* \cdot \exp(-\frac{E^*}{T}) , \qquad (1)$$

where p^* and E^* are the pion c.m. momentum and total energy, respectively.

Figure 1 shows the c.m. spectra of negative pions produced in inelastic CC and CTa interactions. For equal mass CC interactions the center-of-mass system is the CMS of nucleon-nucleon collisions. For unequal mass (asymmetrical) nuclear interactions we have used the CMS of participant protons/5/ which is calculated for each interaction. The dashed lines represent the approximation of the spectra using Eq.(1). In this case the agreement with the experimental data is not satisfactory (the value of $\chi^2/n.d.f.$ has been changed within the limits from 2. to

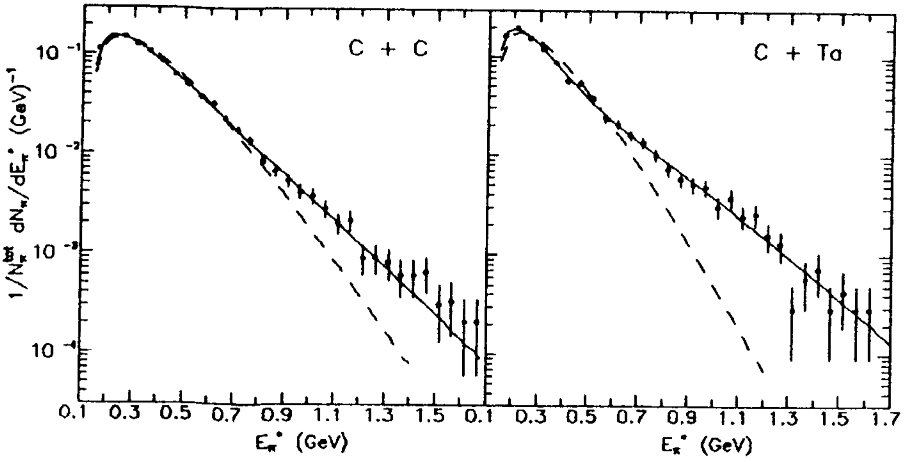

Fig. 1. Noninvariant c.m. energy spectra of negative pions in inelastic CC and CTa interactions. The dashed lines represent a one-temperature fit (Eq.1); and the solid one, a two-temperature fit of the experimental data

Table II. Pion temperatures (T) and relative contributions (R) in (d, α, C) + C and (d, α, C) + Ta interactions

A_i	A_t	T_1 (MeV)	R_1 (%)	T_2 (MeV)	R_2 (%)	$\chi^2/n.d.f.$
d	C	89±4	91±7	190±33	9±7	12/21
α		94±6	85±11	173±22	15±11	15/28
C		83±3	79±6	145±7	21±6	21/29
		60±10*	53±20*	112±10*	47±20*	16/17*
d	Ta	60±10	60±23	118±14	40±23	17/15
α		67±9	80±21	138±28	20±21	12/16
C		66±2	88±3	159±6	12±3	14/24
		42±8*	58±27*	99±9*	42±27*	5/12*

* The temperatures and relative contributions for pions emitted at 90±10° in the CMS of CC and CTa collusions

Table III. Pion temperatures (T) and relative contributions (R) in CC and CTa interactions with different number of participant protons

Interaction	CC			CTa		
N_{part}	0÷2	3÷6	>7	0÷10	11÷25	>25
T_1 (MeV)	89±11	74±7	79±7	71±8	68±2	56±3
R_1 (%)	78±26	61±13	72±15	79±16	90±4	83±7
T_2 (MeV)	136±29	128±8	136±13	146±21	168±10	134±8
R_2 (%)	22±26	39±13	28±15	21±16	10±4	17±7
$\chi^2/n.d.f.$	20/21	20/22	24/26	15/17	17/20	15/20

15.). We have obtained a good approximation using two-temperature fits shown by solid lines. An analogous situation is also observed for the other pairs of colliding nuclei.

The temperature values of negative pions and the corresponding contributions obtained for inelastic collisions of light d, α and C nuclei with carbon and tantalum targets are presented in Table II. Relative contributions, R (%), of the different temperatures to pion multiplicity were calculated over the total c.m. energy interval ($R_i = c_i/(c_1 + c_2)$, where $c_i = \mathrm{const}_i \cdot \int \exp(-E^*/T_i)dE^*$, $i = 1,2$). It is seen that the obtained temperature values do not differ significantly from one another for various pairs of colliding nuclei.

To compare our results with the data of paper[2], the obtained temperatures of pions emitted at 90±10° in the CMS of CC and CTa collisions are also shown in Table II. We can state an agreement of the temperature values of negative pions produced in CC and CTa collisions at 3.36 GeV/N with the Ar + KCl data at 2.1 GeV/N.

Nontrivial properties of nuclear matter are expected at extremely high densities which are accessible in heavy ion central collisions. As is shown in papers[6,7], the net charge of secondary particles Q is an effective measure of collision «centrality». The value of Q determines the number of participant protons from the projectile and target nuclei, N_{part}.

In the experiment we have analysed the noninvariant c.m. energy spectra of pions produced in inelastic CC and CTa interactions with different values of N_{part} and have obtained the following results (see Table III): i) the two-temperature shape similar to that observed for unbiased events is the most preferable approximation of the experimental spectra; ii) the extracted temperature values within the obtained errers are close to the ones presented in Table II for unbiased events; iii) no systematic dependence of temperature values on the impact parameter has been found both in CC and CTa collisions. These results are in agreement with the conclusion of paper[8] concerning a weak dependence of the inclusive distributions of pions on the centrality of light ion collisions.

IV. Comparison with the Quark-Gluon String Model

The models which have taken into account the decay of baryonic resonances showed[12,13] their usefulness for the interpretation of the experimental data on pion production. The comparison with the calculations of the quark-gluon string model (QGSM) can help us to understand the observed features of the c.m. energy spectra as well as to test the validity of the model, and we briefly discuss below the main points of the meson production mechanism in QGSM.

A. Some features of the quark-gluon string model

A good agreement of the Dubna cascade model (DCM)[9] calculations with the experimental data on inclusive characteristics and correlations of secondaries has been shown in previous papers[3]. In this paper we

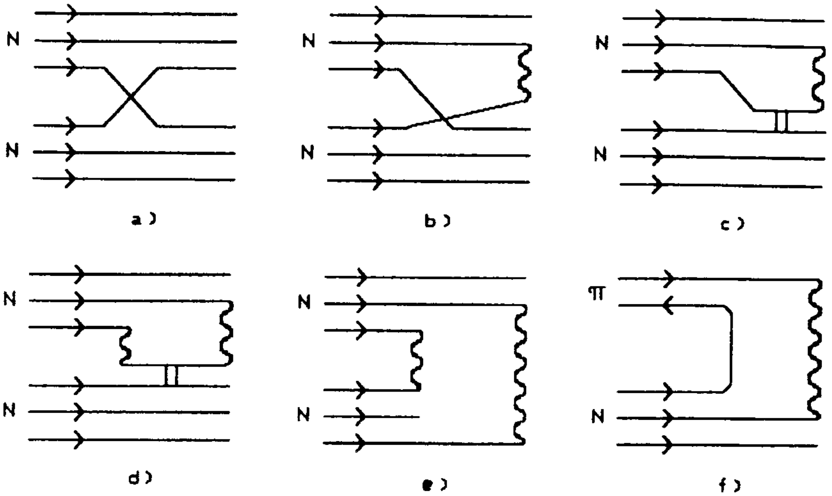

Fig. 2. Topological quark diagrams for main processes taken into account in the model at $\sqrt{s} \leq 4$ GeV: a — binary, b — «undeveloped» cylindrical, c — and d — diffractive, e — cylindrical, f — planar. Solid lines mark quarks and the wave ones show strings

have used the following generation of DCM: the quark-gluon string model (QGSM)/10/.

The model is presented in detail in papers/10,11/. 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-lived resonances. Resonant $\pi + N \rightarrow \Delta$ reactions and pion absorption by NN-quasi-deuteron pairs as well as $\pi + \pi \rightarrow \rho$ 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. We have used the same title of the model because the formalism developed at high energies was as a whole maintained, although the contribution of the string mechanism is insignificant. The masses of the «strings» produced at $\sqrt{s} = 3.14$ GeV were still small (usually not greater than 2 GeV), and they were fragmented mainly (~90%) through two-particle decays.

The included processes are illustrated in Fig.2 for the case of NN interactions. Similar processes also describe πN collisions along with additional reaction (1f) corresponding to the planar quark diagram.

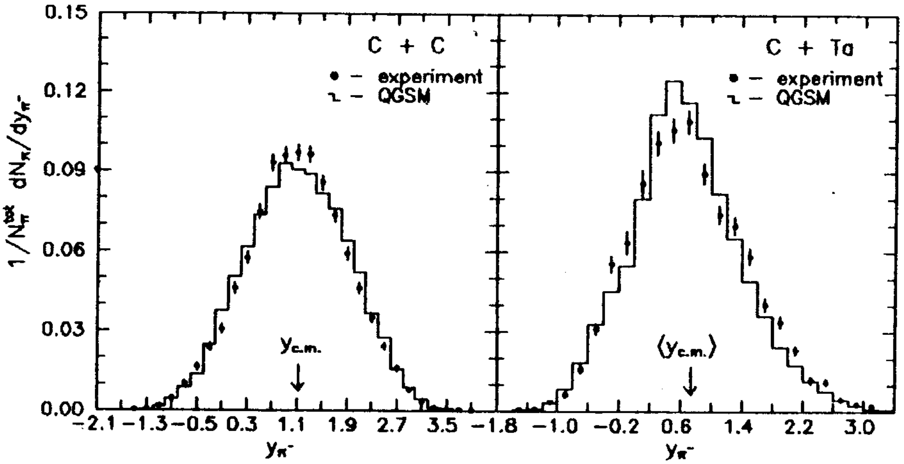

Fig. 3. Rapidity distributions of negative pions produced in CC and CTa collisions. The QGSM calculations are presented by histograms

Binary process (1a) makes a main contribution which is proportional to $1/p_{lab}$. It corresponds to quark rearrangement without direct particle emission in the string decay. This reaction predominantly results in the production of resonances (for instance, $p + p \rightarrow n + \Delta^{++}$) which are the main source of pions. The angular dependence for reaction (1a) can be parametrized 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 the inelastic cross section, which however decreases with decreasing p_{lab}, come from the 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 the following: string motion on the whole as a result of transverse motion of constituent quarks and $q\bar{q}$ production in string breakup. The transverse motion of quarks inside hadrons was described by the 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 the CMS of the string follow the 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 the additive quark model/14/ (for meson-meson cross sections, etc.) were used to avoid data deficiency. The resonance interaction cross sections were taken to be equal to the interaction cross sections of stable particles with the same quark content. The tabulated width of the resonances was used as well.

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 excited recoil nuclear fragments and coalescence of nucleons were not included. The QGSM was used to generate 15.000 CC and 3.000 CTa inelastic minimum bias interactions.

The quark-gluon string model describes the experimental inclusive distributions of negative pions satisfactorily, except multiplicity of secondaries. The model significantly overestimates the number of secondary pions in nuclear collisions with heavy target. Figure 3 demonstrates the normalized to unit pion rapidity spectra produced in inelastic CC and CTa collisions in the experiment. The histograms represent the QGSM calculations. The center-of-mass system position denoted by arrows corresponds to the maximum value of dN/dy_{π}.

B. Analysis of the non-invariant c.m. energy spectra

The histograms in Fig.4 show the c.m. spectra of negative pions generated by means of QGSM. The momenta of pions in the model were corrected for experimental momentum resolution. One can see that the model spectra quantitatively agree with the data. The lack of high E^* pions is more pronounced in CC collisions whereas in CTa interactions the excess of low energy π^- meson is observed. Using a

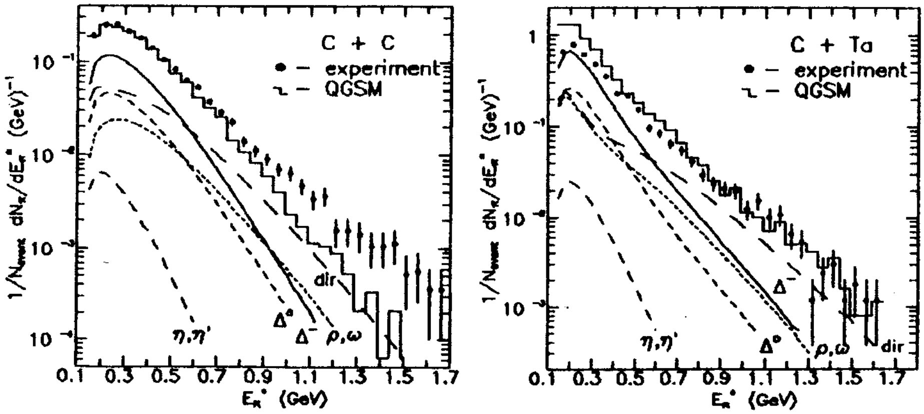

Fig. 4. Noninvariant c.m. energy spectra of negative pions in inelastic CC and CTa interactions. The lines reproduce the smoothed contributions of different sources

Table IV. Temperatures (T) and relative intensities (I) of pions from different sources in QGSM*

	Source	Δ^-	Direct reactions	Δ^0	ρ^-, ρ^0, ω	η, η'
NN	I (%)	35	43	12	7	3
CC	T (MeV)	89	34/123	91	113	64
	I (%)	43	26	17	12	2
CTa	T (MeV)	58/117	39/151	61/117	42/121	63
	I (%)	45	20	17	15	2

*Typical errors of temperatures obtained in the model do not exceed a few MeV (and $\chi^2/n.d.f.$ was about 1.) and were mentioned nowhere in the text. When the one-temperature fit was not satisfactory ($\chi^2/n.d.f. > 2.$), we used two-temperature fit and both temperatures are presented in the table.

one-temperature approximation for both spectra in QGSM we have obtained dissatisfied results ($\chi^2/n.d.f.$ about 5. and 15., respectively). The two-temperature fit similar to that observed in the experiment gives a satisfactory description of the QGSM spectra: $T_1^{CC} = (57\pm7)$ MeV (26%), $T_2^{CC} = (105\pm2)$ MeV (74%), ($\chi^2/n.d.f. \cong 0.5$) and $T_1^{CTa} =$ $= (54\pm1)$ MeV(84%), $T_2^{CTa} = (134\pm3)$ MeV(16%), ($\chi^2/n.d.f. \cong 0.9$). Both in CC and in CTa inelastic interactions the QGSM spectra reproduce the values of temperature lower than in the experiment, and relative contributions of the slopes are significantly different for CC collisions.

In paper/12/ a «two-temperature» shape of the kinetic energy of pions emitted at 90° in CMS of central La+La collisions at 1.35 GeV/N was explained to be due to different contributions of deltas produced at early and late stages of heavy ion reactions. In paper/13/ this effect was quantitatively explained taking into account the finiteness of the number of particles in the statistical ensemble and the resonant absorption mechanisms.

To understand the origin of the two-temperature shape of c.m. energy spectra in the framework of the quark-gluon string model we have used information of the parentage of secondary particles generated in QGSM. As we have mentioned above, dominant sources of pions in QGSM at a considered energies are the decays of Δ and other resonances (ρ, ω, η, η') as well as «direct» reactions. We have marked as «direct»

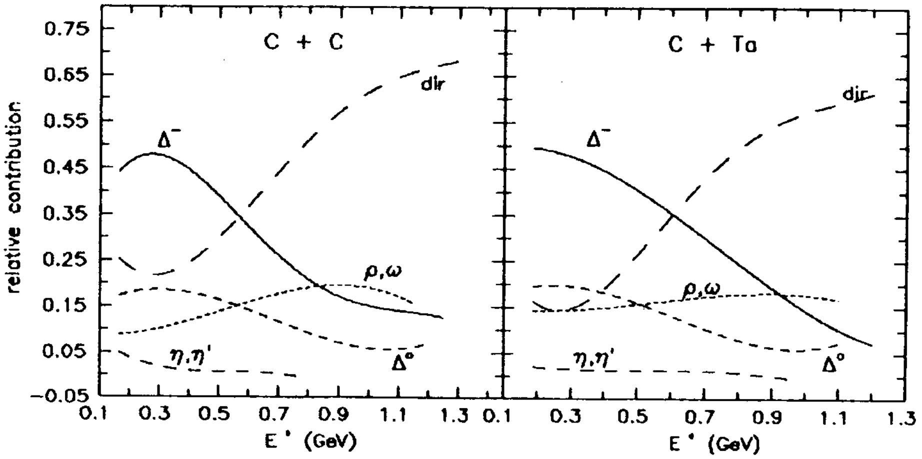

Fig. 5. Dependence of relative contributions from different sources to pion multiplicity in QGSM on the value of pion c.m. energy. Polynomial approximations were used for spectra smoothing

pions not produced in the resonance decays. Table IV presents relative pion intensities I (contributions to π^- multiplicity) for nucleon-nucleon, CC and CTa inelastic interactions generated in QGSM.

Within ~(10—20)% the intensity ratios remain constant for different pion rapidities. The influence of secondary processes in going from nucleon-nucleon (*NN*) to CTa interactions results in resonance production increasing and decreasing a relative contribution of direct reactions. Figure 5 shows relative contributions of the sources normalized to unit in different intervals of the π^--energy spectrum. In fact, it demonstrates the energy dependence of the ratios of the pion E^*-spectra of different sources to the total spectrum of pions in QGSM. As in CC and in CTa collisions the energy dependence of the corresponding relative contributions are approximately identical. At $E^* < 0.5$ GeV the decays of Δ^- are the dominant source of pions (~40% of total pion multiplicity). For higher values of E^* a relative contribution of delta decays decreases, and at $E^* > 0.8$ GeV pions are mainly produced in direct reactions. The total contributions of mesonic resonances (~15%) and Δ^0 decays (~15%) do not change significantly with E^*.

The lines in Fig.4 reproduce the smoothed spectra of the mentioned sources in QGSM with respect to their contribution to the total pion multiplicity marked in Table IV. The spectra display a Boltzmann-like form with unequal slopes and every spectrum was fitted separately using Eq.1 in order to estimate the corresponding value of temperature. The results are presented in Table IV. In CC collisions, except «direct» reactions, the c.m. energy spectra of other sources revealed one temperature. Investigating in detail the sample of «direct» reactions, we have found that each individual type of reaction (e.g. $NN \rightarrow NN\pi$, $\Delta N \rightarrow NN\pi$, etc.) gives the one-temperature shape of c.m. energy spectra.

As distinct from generated CC interactions in CTa collisions, each source of pions demonstrates two slopes of energy spectra. We have studied the c.m. energy spectrum of pions from Δ^- decays and found that the two-temperature shape of pion c.m. energy spectra from delta decays is caused by the growing number of secondary interactions of hadrons inside the heavy tantalum target. It manifests itself in a variety of available Δ^- production channels with different spectra slopes. The slope value is also distorted by a significant increase of intranuclear π^- rescattering.

Thus, in the framework of the quark-gluon string model one can interpret the two-temperature shape of c.m. energy spectra as the result of simple superposition of different source spectra with unequal slopes. In CC collisions the model describes the experimental data to $E^* \sim 0.8$ GeV quite satisfactorily, but at $E^* > 0.8$ GeV the yield of pions produced via the direct mechanism is underestimated in QGSM. At the same time in CTa interactions the excess of low energy pions is observed.

V. Conclusions

The c.m. energy spectra of negative pions produced in inelastic interactions of d, α, C nuclei with C and Ta targets at 4.2 GeV/c per nucleon have been analysed, and the values of temperature have been obtained. The two-temperature shape of the spectra has been observed for any pairs of colliding nuclei.

As a whole, in the collisions of light relativistic nuclei with carbon a temperature value of (80÷90) MeV with a relative contribution to the total pion multiplicity about 85% as well as an additional slope corresponding to a temperature of (140÷190) MeV (15%) are observed. For a tantalum target we have obtained (60÷70) MeV (80%) and

(120÷160) MeV (20%), respectively. The temperatures are close to those for Ar+KCl interactions[2] at 1.8 GeV/N.

The pion temperatures do not depend significantly on the centrality of collisions.

The experimental results are compared with the calculations performed in the framework of the quark-gluon string model. The model reproduces the two-temperature shape of c.m. energy spectra, but it reveals systematically lower values of temperature. The disagreement of the experimental and calculated spectra may be considered to be due to uncertainties in resonance-nucleon interaction cross section (e.g., for the reaction $\Delta N \rightarrow NN\pi$).

The comparison with the model shows that the two-temperature shape of the c.m. energy spectra of pions in the studied nuclear collisions is mainly determined by superposition of partial contributions of different sources (decays of resonances, direct reactions, etc.).

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