Inverses of slopes of invariant inclusive spectra of emitted protons and $\pi^-$-mesons in $^4$HeC and $^{12}$CC interactions with the total disintegration of nuclei.

M. K. Suleimanov [], O. B. Abdinov

*Physics Institute, Azerbaijan Academy of Sciences, Baku, Azerbaijan Republic*

A.I.Anoshin

*Nuclear Physics Institute, Moscow State University, Moscow, Russia*

J.Bogdanowicz

*Soltan Institute for Nuclear Studies, Warzaw, Poland*
and *Joint Institute for Nuclear Research, Dubna, Russia*

A.A.Kuznetsov

*Joint Institute for Nuclear Research, Dubna, Russia*

* Now at the Laboratory of High Energies, JINR, 141980 Dubna, Russia. 

Electronic address: mais@sunhe.jinr.ru
The ideas that extreme states of nuclear matter arise in events with total disintegration of nuclei (TDN) and as these states arise, the properties of events qualitatively change with the number of protons emitted from the nucleus \(Q\), starting from its certain boundary number \(Q^*\), are used in this paper for the experimental search for extreme states of nuclear matter. For realization of these ideas, the invariant inclusive spectra of protons and \(\pi^-\)-mesons as a function of their kinetic energies \(T\) in the lab system for \(^4\)He\(^+\)C and \(^{12}\)CC interactions at the momentum 4.2 A GeV/c with different values of \(Q\) are used. The spectra are fitted by the expressions of the form \(\sum_{i=1}^{n} a_i \exp(-b_i T)\) and the \(Q\)-dependencies of the inverses of slopes \(T_i = 1/b_i\) are studied. It is found that these spectra have two components (the low energy component corresponds to \(T_1\) and the high energy component corresponds to \(T_2\)) and contain the regime change points at \(Q \geq 2\) and 4 for \(^4\)He\(^+\)C interactions and at \(Q \geq 6\) and 9 for \(^{12}\)CC interactions. For protons the first component is mainly connected with the evaporation protons and the leading-stripping fragments produce great influence on \(T_2\). In the TDN region the leading-stripping effect is suppressed and the values of \(T_i\) for \(\pi^-\)-mesons begin to increase with increasing number of protons. We consider this increase to be a signal from the extreme states of nuclear matter. The value of the "temperature" of these states is about 0.140 GeV.

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I. INTRODUCTION

In this paper we discuss the experimental results of studying the invariant inclusive spectra \(f = (\sigma d^3\sigma/dp^3)\) of protons and \(\pi^-\)-mesons as a function of their kinetic energies \(T\) in the laboratory system of coordinates. The spectra \(f(T)\) were obtained for \(^4\)He\(^+\)C and \(^{12}\)CC interactions at the momentum 4.2 GeV/c with a different number of protons.

The aim of this paper is to reveal experimentally the extreme states of nuclear matter in interactions of relativistic light nuclei. The investigation of the states is the most
important trend in relativistic nuclear physics. The primary aim of these investigations is experimental observation of the theoretically predicted phenomenon of nuclear matter deconfinement and transition to the quark-gluon plasma [1].

It is assumed that these states can arise at definite (critical) values of energy density $\varepsilon$ ($\varepsilon_c$) or "temperature" $T_0$ ($T_{0c}$). The values of $T_0$ can be determined only in definite kinematic regions (e.g., in the region of large angles or large $p_t$, etc.) and in the framework of some model-dependent assumptions (e.g., of the chemical potential etc.). Experimental determination of $\varepsilon$ is practically impossible (because of the absence of information on the size of the radiation region). It can only be calculated in the framework some theoretical models. The number of participant nucleons of colliding nuclei is the experimentally determinable quantity closest to $\varepsilon$ [3]. This quantity also cannot be unambiguously found in the experiment because of the absence of full information on the evaporation protons and stripping fragments.

We used the following ideas for the experimental search for the extreme states of nuclear matter:

1. These states can arise in events with the maximum number of protons $Q$ and therefore they are accompanied by the processes of total disintegration of colliding nuclei (TDN).

2. As these extreme states arise, the properties of events must qualitatively change with $Q$ beginning with a definite boundary value $Q \rightarrow Q^*$ (the experimentally obtained values of $Q^*$ will characterize the values of $\varepsilon_c$). The experimental results obtained in [4] point to validity of this idea and the values of $Q^*$ were used for selection of events with TDN on condition that $Q \geq Q^*$.

Experimentally, these ideas are realized by studying the dependence of different characteristics of nucleus-nucleus interactions on $Q$.

In the present paper, to search for the extreme states of nuclear matter the $Q$-dependence of $T_i$ - the inverses of the slopes of $f(T)$ - were studied. Among the experi-
mentally determinable variables $T_i$ is the closest to $T_0$. This quantity can be represented as a sum of energies corresponding to $T_0$ and the energy due to motion of the system itself. One can expect that in the region of large $Q$ the motion energy will tend to zero. Therefore, on transition to the studied region of large $Q$ - to processes of TDN - the values of $T_i$ will become close to $T_0$.

For this, the spectra of $f(T)$ were separately studied for events with different numbers of protons $Q$. It is known that (see for example [5]) the spectra $f(T)$ have the exponential form with a good accuracy. Therefore, to study the dependence of $f(T)$ on $Q$ we fitted these spectra by the expressions of the form

$$\sum_{i=1}^{n} a_i \exp(-b_i T_i).$$

(1)

(here $a_i$ and $b_i$ are the fitting parameters. The quantity $n$ is defined from the condition of the best fitting - the errors in defining $a_i$ and $b_i$ and the values of $\chi^2$ per degree of freedom are the smallest) and studied the dependence of $T_i = 1/b_i$ on the variable $Q$.

**II. EXPERIMENTAL DETAILS**

In this paper the experimental data were obtained by exposing the 2-m propane bubble chamber of LHE JINR to the beams of light relativistic nuclei at the Dubna Synchrophasotron at a momentum of 4.2 A GeV/c. The chamber was placed in a magnetic field of 1.5 T. The statistics are $4852 ^4HeC$ and $7327 ^{12}CC$ interactions (for methodical details see [6]). We had the $4\pi$ geometry for measurement and detected practically all secondary particles. However, it is necessary to note that in our experiment protons are identified by ionization and their range in the momentum interval 0.15-0.50 GeV/c. The protons with the momenta $p < 0.15$ GeV/c have the range less than 2 mm and most of them are not seen in a photo. For all positive particles with the momenta higher than 0.5
GeV/c we introduced the weight that determined the probability for the particle to be a proton or a \( \pi^+ \)-meson. The characteristics of the \( \pi^+ \)-meson were used for determination of the weights. The smallest momentum for detection of \( \pi^- \)-mesons was 0.07 GeV/c. The contamination by electrons and by negative strange particles did not exceed 5% and 1%, respectively.

In this paper the variable \( Q \) is used to determine the number of protons. We defined \( Q \) for each event as

\[
Q = N_+ - N_{\pi^-}.
\]

(2)

where \( N_+ \) is the number of positive particles and \( N_{\pi^-} \) is the number of \( \pi^- \)-mesons (we assumed \( N_+ = N_{\pi^-} \)). Experimental losses of particles and errors in identification of secondary particles influenced the accuracies of determination of \( Q \). The poor accuracy in determination of \( Q \) can lead to appearance of "wrong" \( Q^* \) and to expansion of the regime change regions. For this reason we cannot determine the number of the regime change regions and the exact values of \( Q^* \). For decreasing the influence of this circumstance, we do not consider the groups of events with definite values of \( Q \) but we consider the groups of events with \( Q \geq \). It is known that setting up the experiment like this one decreases the influence of the accidental processes. Therefore, we divided the available statistical material into groups of events with the following values of \( Q \):

\[
Q \geq 1; 2; 3; 4; 5; 6; 7.
\]

(3)

for \( ^4HeC \) interactions and

\[
Q \geq 1; 2; 3; 4; 5; 6; 7; 8; 9; 10; 11.
\]

(4)

for \( ^{12}CC \) interactions and for each group of events the spectra of \( f(T) \) were obtained.

III. THE RESULTS AND DISCUSSION
The spectra of $f(T)$ for $^{12}CC$ with $Q \geq 1;3;6;9$ are shown in figs. 1a,b. (solid lines demonstrate the results of the best fitting). One can see that these spectra have an exponential form. The spectra obtained at other values of $Q \geq$ and the spectra for $^4HeC$ interactions have a similar form. Therefore, all spectra were fitted by expression (1).

It turned out that $n = 2$ in all cases considered (in table 1 the values of $\chi^2$ per degree of freedom are given), i.e., these spectra have two components - the low-energy component corresponding to $T_1$ and the high-energy component corresponding to $T_2$. This result is a well-known experimental fact (see for example [5] and references therein) and is interpreted as an indication of the presence of two sources (or mechanisms) of emission of the observed particles.

The $Q$-dependence of $T_i$ is shown in figs. 2a,b-3a,b. It is seen that for protons
- the values of $T_1$ (fig. 2a) reach 30 MeV at maximum and weakly decrease with growing mass of the projectile nucleon-interaction energy. This result agrees with the conclusions [5] that the low-energy part of the proton spectra is mainly connected with the evaporation protons. The decrease in $T_1$ with growing $Q$ is due to increasing energy loss for secondary interactions;
- the values of $T_2$ (fig. 2b) sharply increase with growing mass of the projectile nucleon-interaction energy.

The regime change points are observed at $Q \geq 4$ and 6 for $^4HeC$ interactions and $Q \geq 8$ for $^{12}CC$ interactions. This result confirms our basic idea (see Introduction) and is in good agreement with the conclusions [6], where similar regime change points were found from the analysis of the probability of $Q$ distributions of events and the dependencies of the mean characteristics of events on $Q$. In [6] the values of $Q$ corresponding to the regime change points were regarded as "critical" ($Q^*$) and were used for separating events with total disintegration of nuclei (TDN) for $Q \geq Q^*$. Note that in the region $Q \leq Q^*$ the values of $T_2$ for protons are almost independent of $Q$ and they sharply decrease in the
$Q \geq Q^*$ region. We think that this is connected with the admixture of leading-stripping fragments to the protons considered. In the region of large $Q$ the leading-stripping effect is suppressed. Against the background of this effect it is difficult to get information on the inner energy (and thus on $T_0$) of nuclear matter since the difference between the values of $T_0$ and leading-stripping particle energy is very large.

From the data in fig. 3a,b it is evident that

- the spectra of secondary $\pi^-$-meson are also well fitted by the expression with $n = 2$ (i.e., there are two sources (mechanisms) of $\pi^-$-mesons emission) and contain the regime change points for $^4HeC$ interactions at $Q \geq 2$ and 4 (fig. 3b) and at $Q \geq 6$ and 9 for $^{12}CC$ interactions (see fig. 3a).

- at the beginning of this spectra of $T_i$ decreases with $Q$ increasing to $Q^*$ and reach its minimum; then, as $Q$ increases in the $Q \geq Q^*$ region, $T_i$ stops decreasing for $^4HeC$ interactions and sharply increases for $^{12}CC$ interactions. It is interesting to note that $T_1$ and $T_2$ similarly depend on $Q$. This indicates that the high-energy and low-energy components of $\pi^-$-mesons differ by that the latter are emitted from the source nearly at rest and therefore they can characterize the states of nuclear matter. We think that it is the values of $T_1$ in the region $Q \geq Q^*$ that correspond to the "temperature" of nuclear matter. Its maximum value $T_1 \simeq 0.140$ corresponds to the "temperature" of nuclear matter in extreme states. If $T_i$ does not increase in the region $Q \geq Q^*$ for $^4HeC$ interactions, it means that the necessary density of energy is not reached in these interactions;

- a decrease in $T_i$ with increasing $Q$ at the beginning of the spectra is due to an increase in secondary interactions and rescattering of $\pi^-$-mesons from intranuclear nucleons, which results in $\pi^-$-meson energy losses. In the $Q \geq Q^*$ region the loss of $\pi^-$-meson energy becomes insignificant. This means that in this region the processes of meson production occur simultaneously with emission of protons, i.e, the collective processes dominate.
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FIG. 1. $T$-dependence of invariant inclusive spectra for protons (a) and $\pi^-$-mesons (b) emitted in $^{12}C C$ interactions. Solid lines are the fitting results. The data are given for events with $Q \geq 1$, $Q \geq 3$ (the corresponding values of $f(T)$ are divided by 100), $Q \geq 6$ (the corresponding values of $f(T)$ are divided by 10000), $Q \geq 9$ (the corresponding values of $f(T)$ are divided by 1000000).

FIG. 2. $Q$-dependence of $T_1$ (a) and $T_2$ (b) for protons emitted in $^4\text{He} C$ (●) and $^{12}C$ (○) interactions.

FIG. 3. $Q$-dependence of $T_1$ (a) and $T_2$ (b) for $\pi^-$-mesons emitted in $^4\text{He} C$ (●) and $^{12}C$ (○) interactions.
TABLE I. The values of $\chi^2$ per degree of freedom

| Q | $^4\text{HeC}$ | $^{12}\text{CC}$ |
|---|----------------|------------------|
|   | $\pi^-$ | $p$ | $\pi^-$ | $p$ |
| 1 | 1.17 | 2.64 | 0.61 | 2.29 |
| 2 | 0.60 | 2.45 | 0.56 | 2.18 |
| 3 | 1.33 | 2.10 | 0.64 | 1.94 |
| 4 | 0.90 | 2.33 | 0.64 | 1.70 |
| 5 | 0.73 | 2.01 | 0.73 | 1.44 |
| 6 | 0.47 | 0.93 | 0.58 | 1.22 |
| 7 | 0.81 | 1.02 | 0.54 | 0.92 |
| 8 | - | - | 0.55 | 1.72 |
| 9 | - | - | 0.39 | 1.35 |
| 10 | - | - | 0.61 | 1.65 |
| 11 | - | - | 0.56 | 1.54 |
