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Formation of relativistic non-viscous fluid in central collisions of protons with an energy of 0.8 TeV with photoemulsion nuclei

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Abstract: By the methods of mathematical statistics we test a qualitative prediction of the old theory of relativistic hydrodynamics non-viscous liquid which can be used as a part of the process of hadronization within the modern hydrodynamical approach for the description of the quark-gluon plasma. Experimental data on the interaction of protons with the energies of 0.8 TeV with emulsion nuclei are used. Results do not contradict the formation of relativistic ideal non-viscous liquid in rare central collisions.

Keywords: Proton, Photoemulsion, Central Collisions, Hadronization, Parametrically Invariant Variables, Non-Viscous Fluid

1. Introduction

In the ion-ion collisions at CERN and RHIC it was discovered a collective properties of the quark-gluon medium, which manifests itself in the possibility of the quarks and gluons to free themselves off nucleons, interact strongly with each other and quite a long time to move as a unit. This movement is well described within the hydrodynamic theory of liquids of low viscosity, which is formed in the central collisions of ions (see reviews [1, 2]). Such a hot quark-gluon plasma (QGP) expands and cools to a temperature $T \approx \mu c^2$ (μ is a pion mass). This results in the more "cold" hadrons. Hadronization of quarks and gluons is a serious yet insuperable theoretical problem. Therefore, the hydrodynamic approach in the stage of hadronization uses the fitting parameters (see [1].) Therefore, it might be useful to use old result related to the hydrodynamic theory, which seems logically to fit into the model of the modern approach to the hadronization of QGP. Namely, for a description of the second stage of hadronization, when the temperature is close to $T \approx \mu c^2$, but QGP has already started to form hadrons, among which there is still a colored interaction, that is, these hadrons still yet form a substance with the properties of the relativistic non-viscous liquid. This state of substance is considered as the starting point in the Landau approach [3, 4], which showed that, in this case, after further expansion of matter according to the laws of relativistic hydrodynamics of non-viscous liquid, the not interacting each other hadrons are born according to the Gaussian distribution on the quasirapidity $\eta = -ln\, tg\frac{\theta}{2}$, where θ is the polar angle of the particle. In the modern approach, like it was in [3, 4], the central collisions with the large multiplicity of secondary hadrons are taken into account. However, the presence of fast valence quarks creates the fluctuations [6] of the average values of quasirapidities of the hadrons which are formed from the QGP, where the parton density increases with energy, in particular, due to the production of vacuum pairs of leading to the birth of the relatively soft hadrons. These quasirapidity fluctuations lead to the total non-Gaussian inclusive distribution of particles in all events. A variation of mean quasirapidity does not change the form of the quasirapidity distribution in each event. Therefore, it would be interesting to determine the form of experimental particle distribution on the quasirapidity in the every individual central nucleon-nucleus and nucleus-nucleus collision. It is not possible to verify visually. However, in the mathematical statistics, there are well developed methods using which we can verify that the given distribution has a Gauss type. In this paper we will use these techniques.

Our experimental data (Baton Rouge- Krakow- Moscow-Tashkent Collaboration [5]) are (central) collisions of protons with energies of 0.8 TeV with emulsion nuclei. This energy is less than the energy at which ATLAS [1, 2] collaboration is working, and so the cross section of the hard jet production is small. Thus, the hard jets can not distort [1] the form of quasirapidy distribution. Therefore, at 0.8 TeV energy, this distortion practically will not be. However, in the papers [3, 4] it was predicted that non-viscous liquid can be formed at the incident proton energies above 1 TeV. However, this value is close to the energy at which our experimental data was obtained. Therefore, to test the theoretical predictions for the properties of the relativistic ideal non-viscous liquid, our experimental data can be used.

2. Parametrically Invariant Variables

The theoretical Gaussian distribution $f(\eta)\propto(\sigma\sqrt{2\pi})^{-1}exp\left(-\frac{(\nu-\eta)^2}{2\sigma^2}\right)$ has two parameters (the mathematical expectation ν and variance σ), which depend on the physical conditions that arise in each collision (see [6]). Therefore, for example, the total inclusive theoretical and experimental [5] distributions differ from the Gaussian distribution. The theory of mathematical statistics [7] offers asymmetry g_1 and excess g_2, which do not depend on these parameters ν and σ but they are sensitive to the shape of the distribution:

$$g_1 = m_3 m_2^{-3/2},\ \ g_2 = m_4 m_2^{-2} - 3,$$

$$m_k = \frac{1}{n}\sum_{i=1}^{n}(\eta_i - \overline{\eta})^k\ ,\ \ \overline{\eta} = \frac{1}{n}\sum_{i=1}^{n}\eta_i \qquad (1)$$

Here n is the number of particles in the event (interaction). In order to use an approach proposed by the mathematical statistics, we divide an ensemble [7] of the theoretical central collisions into subensembles so that the number of particles n and the value of ν (the average quasirapidity of particles in the event) would be constant in the events of each subensemble. In this case, if the values of η_1, η_2, ..., η_n are mutually independent in the events of subensemble and distributed according to the Gaussian law with parameters ν and σ, then the distribution of g_1 and g_2 is independent on the parameters ν and σ and uniquely determined by the number of particles n in the event of subensemble. The mathematical expectation and variance of g_1 and g_2 values are [7].

$$\nu_{g_1}(n) = 0\ ,\ \sigma_{g_1}^2(n) = 6(n-2)(n+1)^{-1}(n+3)^{-1},$$

$$\sigma_{g_2}^2(n) = 24n(n-2)(n-3)(n+1)^{-2}(n+3)^{-1}(n+5)^{-1}$$

$$\nu_{g_2}(n) = -6(n+1)^{-1} \qquad (2)$$

and the values of [7]

$$d_1 = \left[g_1 - \nu_{g_1}(n)\right]\sigma_{g_1}^{-1}(n)$$

$$,d_2 = \left[g_2 - \nu_{g_2}(n)\right]\sigma_{g_2}^{-1}(n), \qquad (3)$$

according to the represented form, have the mathematical expectations equal to 0 and variances equal to 1 in each subensemble, and so in an ensemble of all the events.

In accordance with the logic of mathematical statistics, we can group the events with different n into so-called complex tests (groups), containing N of events. Now we use the central limit theorem of the probability theory, namely, when a large N each of the quantities has

$$\overline{d_1}\sqrt{N} = \frac{1}{\sqrt{N}}\sum_{i=1}^{N} d_{1i}\ \ ,\ \overline{d_2}\sqrt{N} = \frac{1}{\sqrt{N}}\sum_{i=1}^{N} d_{2i} \quad (4)$$

approximately a normal distribution with parameters 0 and 1, and its absolute value must be less than two with probability $\approx 95\%$. In the next section we use this theoretical result.

3. Results

We use experimental data [5], which contains 1685 collisions of protons with an energy of $0.8\ TeV$ with emulsion nuclei. For secondary charged particles, the azimuthal angles φ and their emission angles θ with respect to the direction of the projectile were measured. The quasirapidity η of secondary particle is determined by the formula $\eta = -ln\, tg\frac{\theta}{2}$. The average multiplicities of weakly ionizing particles and all charged particles are, respectively, 20 and 25. Particles for which $I < 1.4 I_0$, where I_0 is the ionization along the tracks of singly charged relativistic particles, were taken to be weakly ionizing particles.

If in the event a large number of gray particles are produced, it is likely the result of the intranuclear cascade, rather than a central collision. However, the relativistic particles of ideal non-viscous fluid can be produced in central collisions from the narrow relativistic disks [1, 2]. So in this case we can expect the formation of the largest possible number of weakly ionizing particles and the minimum number of gray particles. This is the first qualitative criterion of the selection of events. The second quantitative selection criterion of events means that each of two values $|\overline{d_1}\sqrt{N}|$ and $|\overline{d_2}\sqrt{N}|$ should be less than two (see section 2).

These criteria are completely fulfilled, that is, $|\overline{d_1}\sqrt{N}| = 2.0$ and $|\overline{d_2}\sqrt{N}| = 0.4$, in eight stars, where the multiplicity of relativistic singly charged particles is $n \geq 55$ and there is a complete absence of gray particles.

Thus, only small fraction of the events meets the criteria of the formation of the relativistic ideal non-viscous fluid. This may be connected with the fact that the energy $E_{lab} = 0.8$ TeV is equal to the minimum energy at which the theoretical prediction was done [3, 4] for, in fact, very rare absolutely central collisions. Moreover, for example, an excess is a moment of high order and so it is very sensitive to the form of (quasirapidity) distribution at the tails of the distribution. Therefore we use a very strict statistical selection criterion. Thus, we can conclude that our result does not contradict the formation of the relativistic ideal non-viscous liquid, and in the same time, shows that it would be interesting to carry out the similar calculations for higher energy. If the result of the comparison will be positive, the theoretical prediction of [3, 4] could be considered as a part of the process of hadronization in the modern hydrodynamic theory of QGP.

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