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PION MULTIPLICITY AS A PROBE OF THE DECONFINEMENT TRANSITION IN HEAVY-ION COLLISIONS

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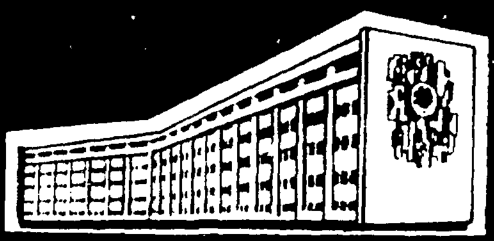

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М.И.Горенштейн,Шин Нан Янг,Чи Минг Ко

Пионная множественность как сигнал деконфайнмента в соударениях тяжелых ионов

Гидрохимическая модель используется для вычисления пионной множественности в релятивистских соударениях тяжелых ионов.Химические реакции учитываются явно на стадии расширения в адронной фазе.Это приводит к отсутствию химического равновесия между адронами и ненулевому значению химического потенциала пионов к моменту теплового замораживания.Мы обнаруживаем специфическую структуру в зависимости пионной множественности от начальной энергии,которая возникает в результате формирования смешанной кварк-адронной фазы на начальной стадии соударения.

M.I.Gorenstein,Shin Nan Yang,Che Ming Ko

Pion Multiplicity as a Probe of the Deconfinement Transition in Heavy-Ion Collisions

The hydrochemical model is used to calculate the pion multiplicity in relativistic heavy-ion collisions.Chemical reactions are explicitly taken into account in the expansion stage of the hadronic phase.It leads to the absence of chemical equilibrium among hadronic particles and a nonzero value of the pion chemical potential at thermal freeze out.We find a specific structure in the incident energy dependence of the pion multiplicity as a result of the formation of the quark-hadron mixed phase in the initial stage of the collision.

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PION MULTIPLICITY AS A PROBE OF THE DECONFINEMENT TRANSITION IN HEAVY-ION COLLISIONS

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Pions are abundantly produced in relativistic heavy-ion collisions and the dependence of the pion multiplicity on the incident energy proves to be an important experimental observable to elucidate the properties of highly excited and strongly interacting matter, see e.g. [1]. The pion multiplicity per participating nucleon was measured in the range of incident energies $E_{lab}/A = (0.5 - 1.8)$ GeV/nucleon[2,3]. According to the suggestions of Ref. [4], these data have been used to probe the nuclear matter equation of state. In a recent paper[5] this consideration has been extended to include the region of the deconfinement phase transition and a plateau-like behaviour of the pion multiplicity has been predicted as a signal for the formation the quark-hadron mixed phase in the initial stage of relativistic heavy-ion collisions.

In both thermodynamical and hydrodynamical models, the final pion multiplicity depends crucially on the specified freeze out conditions. If the freeze out of pions and deltas is assumed to occur at the initial moment of the expansion, then the final pion number will be large. On the other hand, if complete chemical as well as local thermal equilibrium is assumed during the whole expansion process until thermal freeze out, then a smaller pion multiplicity will be obtained. The experimental data suggest that the real situation lies somewhere between these two extremes. The agreement with data can be achieved by assuming that chemical freeze out takes place at baryonic density $n_f^{ch} \cong 2n_o$[6], where $n_o \cong 0.16/fm^{-3}$ is the normal nuclear matter density. But reasonable values of the baryonic density at thermal (particle momenta) freeze out are in the range $n_f^{th} = (0.3 - 0.7)n_o$. It indicates the absence of chemical equilibrium at the later stage of hadronic fireball expansion and this fact should be taken into account in theoretical studies.

In the present note we use the hydrochemical model of Ref. [7] (see also [8]) and include the following "chemical" reactions

$$N + \pi \leftrightarrow \Delta, \quad N + N \leftrightarrow N + \Delta, \tag{1}$$

among pions, nucleons and deltas in the expanding hadronic gas. The hydrochemical equations for spherical fireball expansion are given by[8]:

$$\frac{1}{V}\frac{d}{dt}\{V[\epsilon + \frac{3}{5}\dot{R}^2(\epsilon + p)]\} = 0, \tag{2}$$

$$\frac{1}{V}\frac{d}{dt}(Vs) = -\frac{1}{T}\sum_i \rho_i\psi_i, \tag{3}$$

$$\frac{1}{V}\frac{d}{dt}(V\rho_i) = \psi_i. \tag{4}$$

In the above, R is the fireball radius and $V = \frac{4\pi}{3}R^3$ is its volume; ϵ, p, s and ρ_i ($i = \pi, N, \Delta$) are, respectively, the energy density, pressure, entropy density and particle number densities. The source terms ψ_i in Eqs. (3-5) are defined as in Ref. [8].

For hadronic matter we use the ideal gas equation of state for a gas of pions, nucleons and deltas modified by the excluded volume corrections[9]:

$$p^{excl}(T, \mu_\pi, \mu_N, \mu_\Delta) = p^{id}(T, \tilde{\mu}_\pi, \tilde{\mu}_N, \tilde{\mu}_\Delta)\,, \tag{5}$$

where

$$\tilde{\mu}_i = \mu_i - v_i p^{excl}(T, \mu_\pi, \mu_N, \mu_\Delta)\,,\ \ i = \pi, N, \Delta \tag{6}$$

and T is the temperature, μ_i are the particle chemical potentials and v_i are particle proper volumes introduced in Ref. [9] to account for the effect of hard-core repulsion between hadrons. In contrast with many previous formulations, this gives thermodynamically consistent results. In what follows we assume that $v_i = 4\pi r_i^3/3$, where r_i are the hard-core radii of hadrons. We shall use the values $r_\pi = 0$ and $r_N = r_\Delta \equiv r$ and take r as a parameter in our model. The expression for p^{id} on the righthand side of Eq. (5) is calculated as a sum of ideal gas pressures of pions, nucleons and deltas so that Eq. (5) is an implicit equation for p^{excl}. The particle number densities ρ_i^{excl}, the entropy density s^{excl} and the energy density ϵ^{excl} can be found from Eq. (5) using standard thermodynamical relations:

$$\rho_i^{excl} = (\frac{\partial p^{excl}}{\partial \mu_i})_T = \frac{\rho_i^{id}(T, \tilde{\mu}_i)}{1 + \sum_i v_i \rho_i^{id}(T, \tilde{\mu}_i)}, \tag{7}$$

$$s^{excl} = \sum_i (\frac{\partial p^{excl}}{\partial T})_{\mu_i} = \frac{\sum_i s_i^{id}(T, \tilde{\mu}_i)}{1 + \sum_i v_i \rho_i^{id}(T, \tilde{\mu}_i)}, \tag{8}$$

$$\epsilon^{excl} = \frac{\sum_i \epsilon_i^{id}(T, \tilde{\mu}_i)}{1 + \sum_i v_i \rho_i^{id}(T, \tilde{\mu}_i)}. \tag{9}$$

In the hadronic phase, if we assume chemical equilibrium then we have $\mu_\pi = 0$ and $\mu_N = \mu_\Delta = \mu$ (and consequently $\psi_i = 0$). But these relations can be violated in the course of the hydrochemical expansion governed by Eqs. (2-4).

To describe the quark-gluon plasma phase we use the bag model equation of state (see, e.g. [10]) with massless u,d-quarks and the bag constant $B = 400\,MeV/fm^3$. The pressure is then

$$p_Q(T, \mu) = \frac{37}{90}\pi^2 T^4 + \frac{1}{9}\mu^2 T^2 + \frac{1}{162\pi^2}\mu^4 - B\,, \tag{10}$$

where μ is the baryonic chemical potential. The phase diagram for our two-phase system can be constructed according to the Gibb's procedure for systems with a first-order phase transition. We stress that the inclusion of finite proper volumes of nucleon and delta permits us to overcome the pathology in the usual formulation of quark-hadron phase transition with noninteracting point-like hadrons, where the hadronic phase dominates at high T and/or μ as it has a larger number of degrees of freedom than that in the quark-gluon plasma.

We find reasonable values for the phase transition parameters in $T-\mu$ plane for baryon hard-core radii $r = (0.5 - 0.7)\,fm$ in the hadronic phase as shown in Fig. 1. In Fig. 2, we show the $T-n$ phase diagram (n is the baryonic number density) for $r = 0.65\,fm$. For the mixed phase of quarks and hadrons, the quark and hadron pressures are equal and other thermodynamical quantities are constructed as linear combinations of corresponding quark and hadron ones.

We assume that via the compression shock model a baryon-rich fireball is formed in the central collision of two heavy ions. This picture can presumably be justified by the large stopping power of colliding nuclei at incident energies $E_{lab}/A < 10$ GeV/nucleon. The thermodynamical parameters of our system after compression satisfy the shock adiabat equation

$$n^2 = n_0^2 \frac{(\epsilon + p)(\epsilon + p_o)}{(\epsilon_o + p)(\epsilon_o + p_o)}, \qquad (11)$$

where n_o, ϵ_o and p_o ($\epsilon_0 \cong M_N n_o, p_o = 0$, M_N is the nucleon mass) are parameters of the intial normal nuclear matter state. The point on the shock adiabat is fixed by the incident energy as

$$E_{lab}/A = 2M_N[(\frac{\epsilon/n}{\epsilon_o/n_o})^2 - 1]. \qquad (12)$$

The compression shock adiabat is shown in $T-n$ plane in Fig. 2. The open circles and the numbers near the circles stand for, respectively, the entry points in the phase diagram and the values of the incident energy per nucleon in units of GeV/nucleon. The threshold incident energy for the formation in the initial state a mixed phase is ~ 2 GeV/nucleon and the quark-gluon phase is ~ 4.5 GeV/nucleon. We would like to point out that these threshold energies are meant to illustrate the possible scenarios that occur in relativistic heavy-ion collisions and their values may differ if other models are used.

From a given initial state the fireball expands up to the freeze out at some critical baryonic density which we choose as $n_f^{th} = 0.5\,n_o$. In the quark-gluon and mixed phases we assume both thermal and chemical equilibriums. Therefore the evolution of the fireball will be governed by the equations (2-3) but with vanishing source terms, expressing the energy and entropy conservations, and the baryonic number conservation instead of Eq. (4). For the expansion in the hadronic phase, the source terms are included. So the chemical equilibrium among hadrons can be violated and the total entropy of the fireball becomes a nonconserved quantity.

In Fig. 3, we show the results of our calculation for the pion multiplicity per nucleon, n_π/A, for three different values of baryon radius $r = 0.60$, 0.65 and $0.70\,fm$. The pion multiplicity is calculated as a sum of pion and delta numbers at the thermal freeze-out when the baryonic number density is $n = n_f^{th}$. The total number of pions and deltas decreases in the hadronic expansion stage due to the reactions $\Delta N \rightarrow NN$, but this reaction becomes less effective with decreasing baryonic density. This number therefore freezes out earlier and remains approximately constant until the thermal freeze out. In our calculation this quantity is still slightly larger than experimental values, as seen in Fig. 3. Also, the total entropy of the fireball, which is assumed to be exactly conserved in the quark and mixed phase expansion, increases slightly in the hadronic expansion stage due to chemical nonequilibrium.

The main results shown in Fig. 3 are the following. The final pion multiplicity is rather insensitive to the baryon parameter r if the energy of nuclear collisions leads to initial states of the fireball which are in pure hadron or quark-gluon phases. On the other hand, when the initial state of the fireball is in the mixed phase we find a specific structure in the dependence of pion multiplicity on the incident energy and this effect is rather sensitive to the value of the hard core radius in the hadronic equation of state. For $r > 0.65\,fm$ the pion multiplicity decreases with increasing collision energy. It indicates the instability of the single compression shock (see the discussion of this point in [5,11]). In any case, we observe very different behaviours of the incident energy dependence of the pion multiplicity for the initial fireball states in pure (hadron or quark-gluon) and in mixed phases. It supports the suggestion of Ref. [5] to look for plateau-like structure in pion multiplicity as a signal of the mixed phase formation in relativistic heavy-ion collisions. The physical origin of this phenomenon is the "anomalous" thermodynamical properties of the mixed phase. With increasing initial collision energy the baryonic density and energy density on the compression shock adiabat inside the mixed phase increase but the fireball temperature decreases. Besides the structure in pion multiplicity function this temperature decrease also leads to the suppression of dilepton production in the corresponding range of the initial energies (see [8]). We believe that experimental studies of these signals for the mixed phase are rather promising.

Another interesting result from our calculations is the nonzero value of pion chemical potential μ_π at thermal freeze out. We note that at the initial moment of the expansion in hadronic phase the pion chemical potential is assumed to be zero and it later becomes nonzero as a result of the violation of chemical equilibrium in π, N, Δ system in the hadronic expansion stage. Its value turns out quite large and is in the range of $(120 - 130)$ MeV when the initial fireball states are in the pure hadronic phase. It means that the number of pions exceeds the equilibrium value at the thermal freeze out. It has been suggested [12] that this large values of μ_π may be responsible for the excess of low-energy pions observed in the pion energy spectra in heavy-ion collision at $E_{lab}/A \sim 1$ GeV/nucleon [3,13]. In the framework of the present calculations it becomes possibile to take into account collective flow, delta decay and chemical nonequilibrium effects simultaneously in a selfconsistent manner. The influence of all these effects on the shape of pion momentum spectra will be studied in a separate publication.

In conclusion, we have studied the poin multiplicity in high-energy heavy-ion collisions. Bag model equation of state is employed for quark-gluon phase. For hadrons, the recently developed excluded volume formulation has been used so that a thermadynamically consistent phase diagram is obtained. The initial state of the mattter is determined from the compression shock model while its time evolution is described by the hydrochemical model in which chemical reactions in the hadronic phase are taken into account. It leads to the absence of chemical equilibrium among hadronic particles and a nonzero value of the pion chemical potential at thermal freeze out. A plateau-like structure in the incident energy dependence of the pion multiplicity is obtained, when the initial states are in the mixed phase of hadrons and quarks. This supports the suggestion of Ref. [5] and it is thus interesting to use the pion multiplicity as a probe of the onset of deconfinement transition in heavy-ion collisions.

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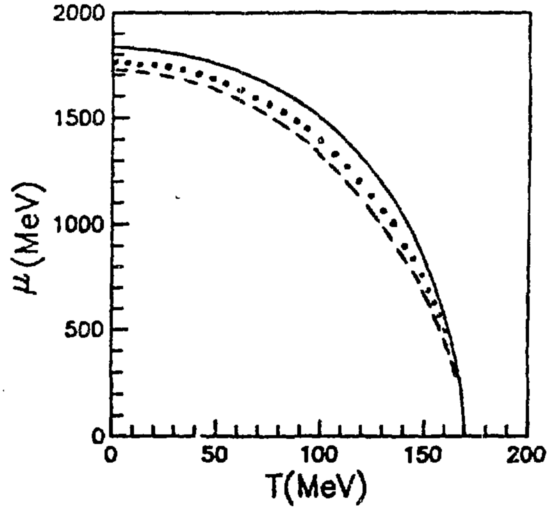

Fig. 1. **Phase diagram in the $T-\mu$ plane. The solid, dotted, and dashed curves correspond to baryon radius parameter r = 0.60, 0.65 and 0.70 fm, respectively.**

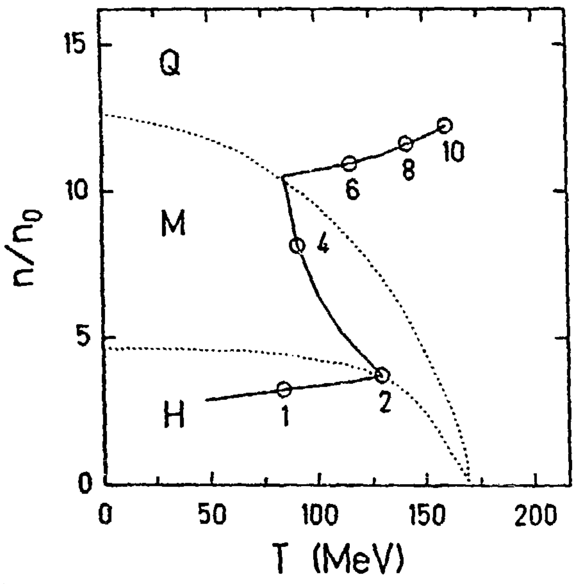

Fig.3. The incident energy dependence of the pion multiplicity per nucleon.The solid,dotted,and dashed curves denote results obtained with baryon radius parameter $r = 0.60$, 0.65 and 0.70 fm, ,respectively.The data points given by the open squares are from Refs. [2,3].

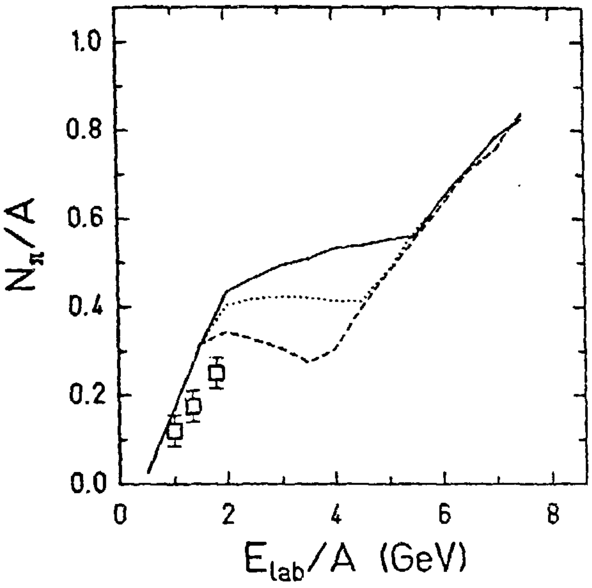

Fig.2. Phase diagram(dotted curves) in the T-n plane.The solid curve is the shock adiabat with the numbers near the open circles being the incident energies in GeV/nucleon.

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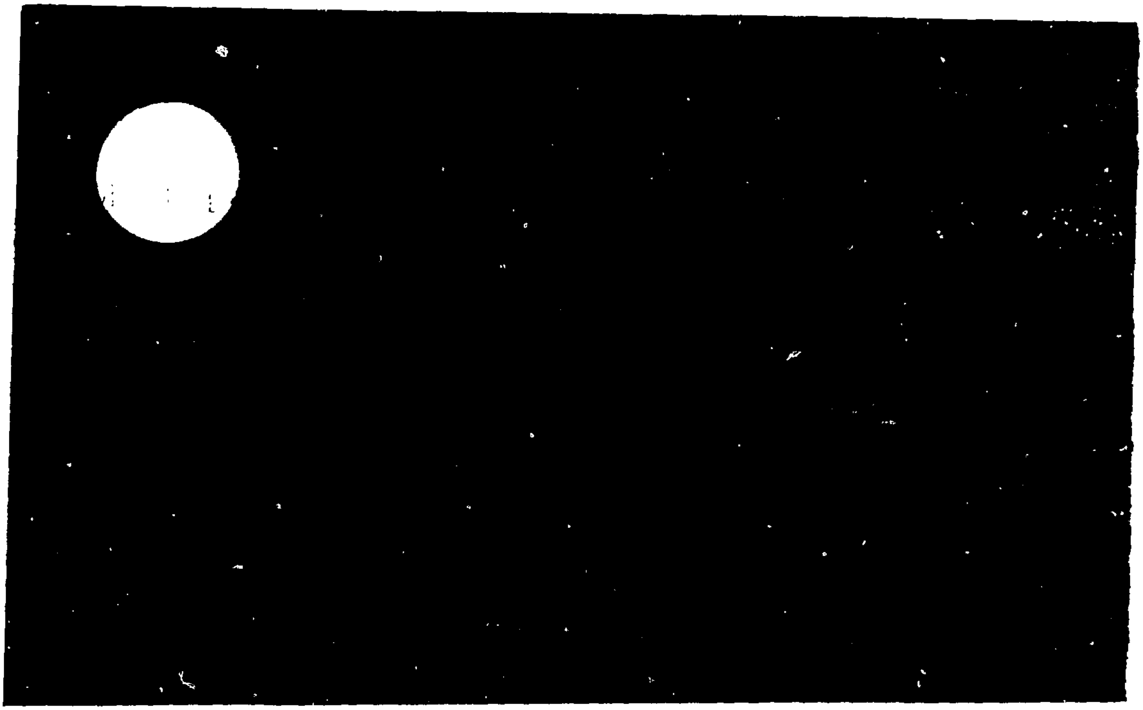

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