The deconfinement phase transition and behavior of the pion multiplicity in nuclear collisions

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In the formation of the mixed quark-hadron phase in nucleus–nucleus collisions there is a special shock wave configuration which leads to a plateau-type behavior of the pion multiplicity as a function of the collision energy. This behavior can serve as a new qualitative signal of the deconfinement phase transition.

The shock-wave compression model for nucleus–nucleus collisions (see, for example, Ref. 1) is based on the general laws of energy-momentum flux and baryon number conservation. At laboratory energies $E_{\rm lab}^{\rm kin}/A < 10$ GeV/nucleon the stopping power of nuclei is apparently sufficient for the validity of this treatment, at least for central collisions of nuclei with large atomic number A. The deconfinement phase transition should then occur at relatively low initial energies of 2–6 GeV/nucleon (Ref. 2) and the region of the mixed quark–hadron phase with thermodynamically anomalous properties[3] of the equation of state can be reached. The usual shock wave is then unstable,[2–5] and instead of it stable configurations of several simple waves and shock waves appear.[6–7] It was noted long ago[8] that information on the equation of state of nuclear matter can be obtained from the data on the pion multiplicity in heavy ion collisions. The purpose of the present study is to show that the pion multiplicity as a function of the collision energy of the nuclei can signal the deconfinement phase transition. However, it should be noted that obtaining numerical values for the pion multiplicity in the hydrodynamical approach essentially depends on the "chemical quenching" conditions, which should be studied separately (see Ref. 9).

To describe hadronic matter, we use the equation of state proposed in Ref. 7, which generalizes the usual mean field theory (see, for example, Ref. 10) and is normalized to the properties of normal nuclear matter with compressibility equal to 300 MeV (Ref. 11). An important feature of our treatment in the calculation of the pion multiplicity is the introduction into the equation of state of delta particles of finite width. We do this within the framework of the thermodynamically self-consistent scheme proposed in Ref. 12. We describe the quark-gluon plasma phase using the bag model (see, for example, Ref. 13) with massless u and d quarks and vacuum constant $B = 235$ MeV.[4] The full phase diagram in the thermodynamical "temperature–baryon number" plane is constructed using the usual Gibbs criterion for systems with a first-order phase transition.

The thermodynamical parameters of the system arising as a result of a central collision of two nuclei (after the passage of shock waves) is determined by the equation for the shock adiabat or Rankine-Hugoniot-Taub adiabat (RHTa) $p(x)$

$$n^2X^2 - n_0^2X_0^2 - (p - p_0)(X + X_0) = 0, \tag{1}$$

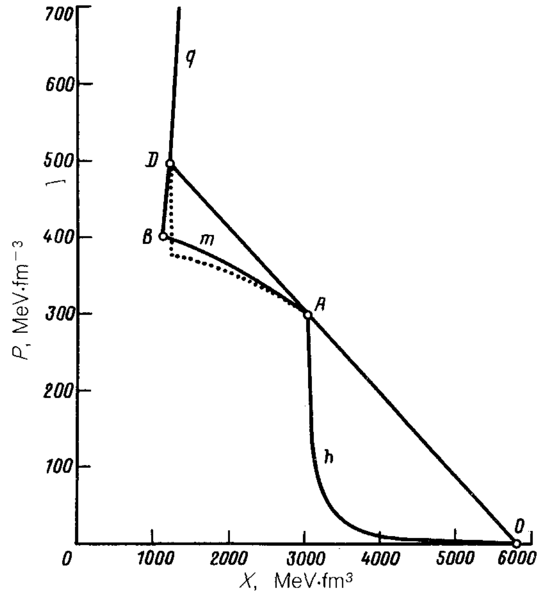

FIG. 1. The solid line shows the shock adiabat (RHTa) for hadronic matter (h), quark matter (q), and the mixed phase (m). The center of the RHTa corresponds to the ground state of nuclear matter (0). The segment ABD on the RHTa corresponds to unstable shock transitions and should be replaced by the dotted line—the generalized shock adiabat.

where p is the pressure, n is the baryon number density, $X \equiv (\epsilon + p)/n^2$ is the generalized specific volume, and ϵ is the energy density. The parameters $p_0 = 0$, $n_0 = 0.16$ F^{-3}, $X_0 = 5800$ MeV·fm^3 correspond to the ground state of nuclear matter. The results of our calculations are shown in Fig. 1. The state of the system determined by a point of the RHTa depends on the collision energy per nucleon through the equation (M_N is the nucleon mass)

$$E_{\rm lab}^{\rm kin}/A = 2M_N \left[\left(\frac{\epsilon/n}{\epsilon_0/n_0} \right)^2 - 1 \right]. \tag{2}$$

We find that all the points of segment ABD of the RHTa correspond to unstable shock transitions. The stable physical solution of the hydrothermal problem is in this case the generalized shock adiabat proposed in Ref. 6. One important part of the generalized shock adiabat (the Possion adiabat) corresponds to a configuration consisting of a shock wave and a simple compression wave. The amplitude of the shock wave for all the states of this configuration is fixed (a shock transition connects the points O and A), and the value of s/n (where s is the entropy density) is a constant in the simple wave. This causes the total of the system to be constant in some range of collision energies (see Refs. 6–7 for more details about the generalized shock adiabat).

To calculate the pion multiplicity, we propose an adiabatic expansion ($s/n = \text{const}$) of our system up to the time of chemical quenching. In Ref. 14 it was

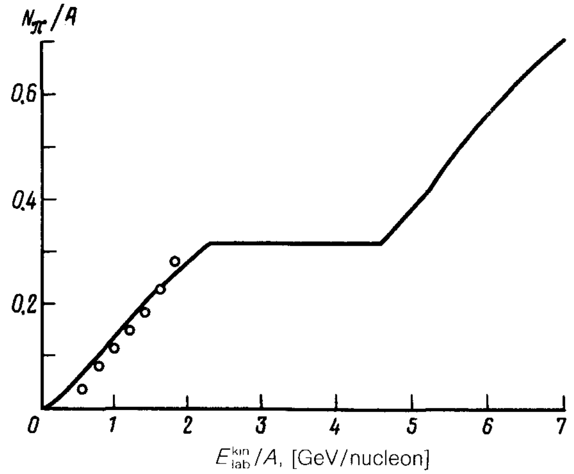

FIG. 2. Multiplicity of π mesons as a function of the energy per nucleon in nuclear collisions. The solid line is the result of the calculation with $n_f = 1.75n_0$. The points are the experimental data from Ref. 15.

shown that the possible increase of s/n due to deflagration shock waves in the expansion process is no larger than several percent. The pion multiplicity per nucleon is then given by the expression

$$N_\pi/A = \left(\frac{n_\pi + n_\Delta + n_{\bar{\Delta}}}{n}\right)_f, \tag{3}$$

where n_π and $n_{\Delta(\bar{\Delta})}$ are the number densities of thermal pions and (anti)deltas at the time of chemical quenching. The value of (3) decreases in the expansion process and therefore depends on the quenching density. In Ref. 9 it was shown that the pion multiplicity is consistent with the experimental data if the chemical quenching occurs at baryon densities roughly equal to twice the normal nuclear density. Treating the baryon number density in the chemical quenching n_f as a free parameter, we obtain good agreement with the available experimental data on $N\pi/A$ (for initial energies of $E_{\rm lab}^{\rm kin}/A < 2$ GeV/nucleon) when $n_f = 1.75n_0$. The complete curve for N_π/A as a function of $E_{\rm lab}^{\rm kin}/A$, including our predictions for higher energies, is shown in Fig. 2.

The result of this article is the prediction of the plateau structure in the pion multiplicity as a function of the nuclear collision energy. This result occurs in the formation of the mixed quark-hadron phase and can be viewed as a new qualitative signal of the deconfinement phase transition. This prediction can be checked in experiments at the Dubna nuclotron, which (we hope!) will be carried out in the very near future.

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[1]H. Stocker and W. Greiner, Phys. Rep. **137**, 277 (1986).
[2]K. A. Bugaev and M. I. Gorenstein, Z. Phys. C **43**, 261 (1986).
[3]K. A. Bugaev, M. I. Gorenstein, and V. I. Zhdanov, Z. Phys. C **39**, 365 (1988).
[4]B. Kämpfer, H. W. Barz, and L. P. Csernai, Report No. UMTNP-115/1984, University of Minnesota (1984) (unpublished).
[5]V. M. Galitskij and I. N. Mishustin, Phys. Lett. **72B**, 285 (1978); J. Hofmann, B. Muller, and W. Greiner, Phys. Lett. **82B**, 195 (1979).
[6]K. A. Bugaev, M. I. Gorenstein, B. Kämpfer, and V. I. Zhdanov, Phys. Rev. D **40**, 2903 (1989).
[7]M. I.Gorenstein, D. H. Rischke, K. A. Bugaev, H. Stöcker, and W. Greiner, Preprint UFTP 239/1989, Frankfurt (1989).
[8]H. Stöcker, W. Greiner, and W. Scheid, Z. Phys. A **286**, 121 (1978); R. Stock *et al.*, Phys. Rev. Lett. **49**, 1239 (1982).
[9]N. K. Glendening, Phys. Rev. C **37**, 14 (1988).
[10]B. D. Serot and J. D. Walecka, Adv. Nucl. Phys. **16**, 1 (1986).
[11]N. K. Glendening, Phys. Rev. C **37**, 2733 (1988).
[12]M. I. Gorenstein, St. Mrowczynski, and D. H. Rischke, Phys. Lett. **243B**, 327 (1990).
[13]J. Cleymans, R. V. Gavai, and E. Suhonen, Phys. Rep. **130**, 217 (1986).
[14]K. A. Bugaev, Preprint ITP-88-169P, Kiev (1989) [in Russian].
[15]J. W. Harris *et al.*, Phys. Rev. Lett. **58**, 463 (1987).

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