ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ СО АН СССР

32

E.V. Shuryak, O.V. Zhirov

IS THE EXPLOSION OF QUARK-GLUON PLASMA FOUND?

PREPRINT 85-121

НОВОСИБИРСК

ABSTRACT

Phase transition from hadronic gas to quark-gluon plasma leads to «softness» of the equation of state and nontrivial explosion-type phenomena, affecting $\langle p_\perp \rangle$ of secondaries. Theoretical estimates reproduce qualitatively main features of recent JACEE observations.

In our Letter written six years ago [1] we have addressed a question of whether available experimental data on high energy pp collisions have shown any sign for collective transverse explosion of excited matter. The method used was based on «Doppler widening» of transverse momentum spectra of various secondaries (π, ϱ, K, K^*, $\bar{p}$, etc.) due to collective motion. It was found that pure thermodynamical description of these spectra «worked too well», providing good fit to data with *no* sign of collective effects. An explanation proposed in [1] has related the absence of collective flow to unusual «softness» of matter in the phase transition region.

Now we return to consideration of the influence of this phase transition on transverse collective expansion. It turns out, that the price for making the matter «soft» in some region is that it becomes very «explosive» nearby, so we make semiquantitative analysis of the resulting effects.

Our present discussion is triggered by recent data obtained by JACEE collaboration [2] on high enegry nuclei-nuclei collisions, which, as we argue below, are in striking correlation to theoretical expectations considered below. Although the observations are based on only few events, the grouth in $\langle p_\perp \rangle$ with energy density of matter is so impressive (see Fig. 1,*a*), that it can hardly be a statistical fluctuation. Note also, that below some critical point $\langle p_\perp \rangle$ is nearly constant, and about the same as observed at SPS $p\bar{p}$ collider (the dashed curve).

We start with brief introduction of some «realistic» equation of state (same as in [1]). At Fig. 2,*a* we plot dependence of pressure p on temperature T. At small T the matter is a hadronic gas, and taking hadronic resonances into account by Beth-Ulenbeck method (see details and references in [3]) one comes to $p(T)$ parametrized by

$$p(T) \simeq AT^6, \qquad A = 20\ \text{GeV}^{-2}. \tag{1}$$

At high T the matter is believed to be nearly an ideal quark-gluon plasma, with the equation of state looks as follows:

$$p(T) = 5.2 \cdot T^4 - B. \tag{2}$$

We attract the reader's attention to the «bag» term B, resulting from the fact that physical QCD vacuum state is lower than «perturbative» one. Instead of MIT fit to hadronic properties in the bag model [4] ($B(\text{MIT}) = 55\ \text{MeV/fm}^3 = 4.3 \cdot 10^{-4}\text{GeV}^4$), we use much better grounded value, suggested by QCD sum rules [5]: $B(\text{sum rules}) = 0.5 - 1\ \text{GeV/fm}^3 = (4-8) \cdot 10^{-4}\ \text{GeV}^4$ (see [6] for recent review). Somewhat rounded value, $B = 1\ \text{GeV/fm}^3$, is taken below.

The equation of state in the intermediate region remains uncertain, but, naively, one may just continue both lines till they cross. It implies rapid transition of the first order, which does not look so harmless on $p(\varepsilon)$ plot shown at Fig. 2,*b* (ε is the energy density). Rapid transition is supported by lattice simulations, and we assume that it is the case.

As we noted in [1], smallness of p/ε ratio (or «softness») is phenomenologically wellcomed. It was pointed out by L. van Hove [7] (see also subsequent works [8]) that this feature of $p(\varepsilon)$ may lead to hydrodynamical instabilities resulting in discontinuities, producing, in principle, significant collective velocities. Now we present semiquantitative estimates of this effect with our «realistic» equation of state.

Note, that in high energy collisions the transverse expansion is strongly limited by duration of longitudinal expansion. Thus, the transverse collective velocity depends on whether the matter is accelerated rapidly enough. That is why instantaneous phenomena like rarefaction shocks are so important.

First of all, with our «realistic» equation of state we indeed have some «window» for these shocks. Not going into details (see [7, 8]) we remind that shock parameters satisfy natural conditions of energy-momentum conservation and positive entropy production, leading to $\left(s = \frac{dp}{dT}\right)$:

$$s_h \frac{(p_h + \varepsilon_q)}{T_h} \geqslant s_q \frac{(p_q + \varepsilon_h)}{T_q}; \tag{3}$$

where subcript h (q) means hadronic (quark) matter. Rapidity of both phases in the front rest frame are as follows

$$\text{th}^2 y_h = \left(\frac{p_q - p_h}{\varepsilon_q - \varepsilon_h}\right)\left(\frac{\varepsilon_q + p_h}{\varepsilon_h + p_q}\right); \quad \text{th}^2 y_q = \left(\frac{p_q - p_h}{\varepsilon_q - \varepsilon_h}\right)\left(\frac{\varepsilon_h + p_q}{\varepsilon_q + p_h}\right);$$

$$\text{th}^2 \eta \equiv \text{th}^2(y_h - y_q) = \frac{(p_h - p_q)(\varepsilon_h - \varepsilon_q)}{(\varepsilon_h + p_q)(\varepsilon_q + p_h)}. \tag{4}$$

Details concerning these shocks are collected at Fig. 3. Its upper part shows temperature of matter after the shock front, as a function of initial energy density. The lower part shows corresponding rapidity of the flow after the shock, if the matter was initially at rest.

It should be emphasized that physics of such shocks is very complicated. For large systems there is no time for the shocks from the surface to come to the center, but they can appear as «bubbles» (see [8a]), containig preheating by compression shocks. Our aim here is to estimate gross velocity without detailed solution of hydrodynamical equations. Effect of ordinary hydrodynamical transverse acceleration is estimated by Newton's second law for transverse system size $R(t)$:

$$\frac{d^2R}{dt^2} \sim \frac{2}{R} \frac{p}{\varepsilon + p}. \tag{5}$$

Another equation expresses energy conservation

$$\frac{d\varepsilon}{dt} = -\frac{(\varepsilon + p)}{t} - 2\frac{(\varepsilon + p)}{R}\frac{dR}{dt} \tag{6}$$

where two r.h.s. terms correspond to longitudinal and transverse expansion, respectively. Here we have assumed that longitudinal expansion is «scaling» one, $v_{\parallel} = x/t$. Equations (5, 6) are integrated numerically from the initial time $t_0 = 0.5$ fm, $R = 1/m_{\pi}$, $\varepsilon = \varepsilon_0$, up to the break-up at temperature $T = 130$ MeV. If the matter reaches the unstable region, we assume that it jumps into low density phase instantaneously in the whole volume.

The effect of collective flow, resulting from ordinary expansion together with discontinuities, is convoluted with thermal $p_{\perp}$-distribution at break-up. Correspondence of Bjorken's observable $\tilde{\varepsilon}$ and true initial energy density ε_0 is seen from upper and lower scales of

Fig. 1. Our resulting curves for $\langle p_\perp \rangle$ are shown in Fig. 1,*b*. It resembles the data very much, and this observation is the central point of the present work.

What further measurements can clarify these important issue? First of all, both the abovementioned manifestations of the phase transition, the temporary absence of the collective flow and subsequent violent «explosion» in the course of increasing $\tilde{\varepsilon}$ should be tested in high-statistics accelerator experiments, now being in preparation. It is very important to compare spectra of different secondaries, so that Doppler nature of widening of transverse momentum distribution be demonstrated. Another crucial test of the mechanism considered can be based on experiments, capable to observe events with higher matter excitation $\tilde{\varepsilon}$. It is predicted that rapid growth of $\langle p_\perp \rangle$ should disappear above the transition region.

Considering A-dependence of the effect we may say that ordinary hydrodynamical expansion leads to smaller acceleration of matter at larger systems (larger A) because pressure gradient is smaller (see Fig. 1,*b*). Shock effect, assumed to be instantaneous, is on the contrary weakly A-dependent.

We are avare of the fact, that nonequilibrium effects, other uncertainties may significantly modify these results. Nevertheless, we expect that main features of the dependence considered will survive. In particular, we attract the reader's attention to the fact that the position of the jump for «realistic» equation of state and for JACEE data nearly coincide. The height of this jump depends on the details, but it is obviously of the same order of magnitude as in these data.

Concluding this letter, we may say that the presence of strong phase transition makes expansion of hadronic matter highly nontrivial, even if one disregard nonequilibrium effects. As a result, even simplest observables (like $\langle p_\perp \rangle$ measured by JACEE group) may provide a very strong signal. This should encourage experimentalists to make further studies of heavy ion collisions at high energies.

REFERENCES

1. *E.V. Shuryak and O.V. Zhirov.* Phys. Lett. 89B (1980) 253.
2. *T.H. Burnett et al.* Characteristics of JACEE heavy ion events at energies above TeV/*N*. Proceedings of «Quark Matter 84», Helsinki. In: Lecture Notes in Physics, N 221, Springer-Verlag.
3. *E.V. Shuryak.* Phys. Rep. 61C (1980) 72.
4. *T. De Grand et al.* Phys. Rev. D12 (1975) 2060.
5. *M.A. Shifman, A.I. Vainstein and V.I. Zakharov.* Nucl. Phys. B147 (1979) 385, 448
6. *E.V. Shuryak.* Phys. Rep. 115C (1984) 152.
7. *L. van Hove.* Z. Phys. C21 (1983) 93.
8. *M. Gyulassi, K. Kajantie, H. Kurki-Sonio and L. McLerran.* Nucl. Phys. B237 (1984) 477.

   N.K. Glendenning and T. Matsui. Phys. Lett. 141B (1984) 419.

   L.P. Csernai. Phys. Rev D29 (1984) 1945.

   B.L. Friman, K. Kajantie and P.V. Ruuskanen. Converting mixed phase into hadrons. Preprint HU-TFT-85-21, 1985.

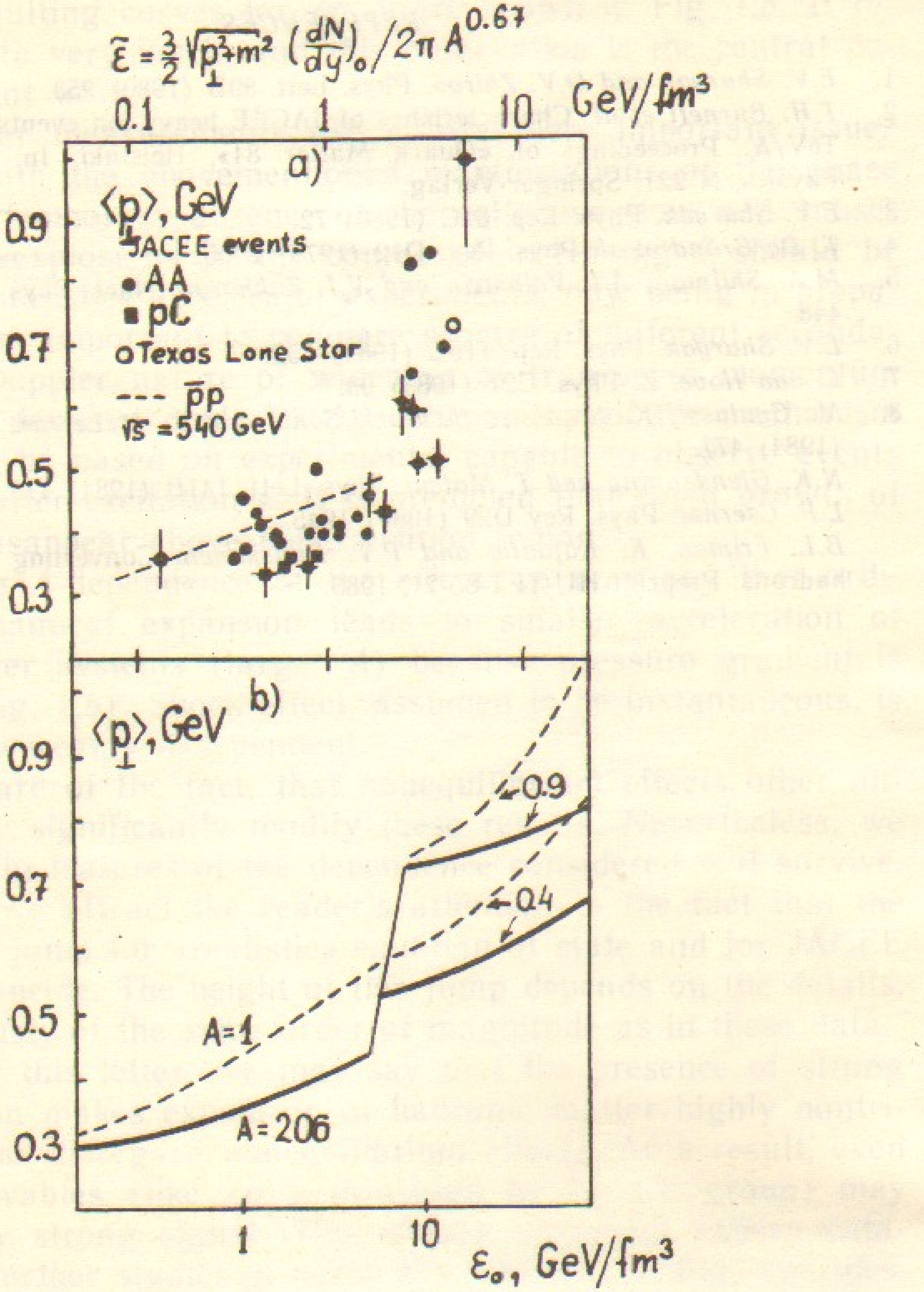

Fig. 1. a —Experimental data on $\langle p_\perp \rangle$ versus initial energy density $\tilde{\varepsilon}$ (Bjorken's estimate), defined as shown at the top of the figure. *b*—Predictions of the model (see text) for $p\bar{p}$- and $PbPb$-collisions (dashed and solid lines, respectively). Various lines at the right from the jump correspond to shocks with maximal and zero entropy production. Numbers given at the figure indicate jumps in flow rapidity.

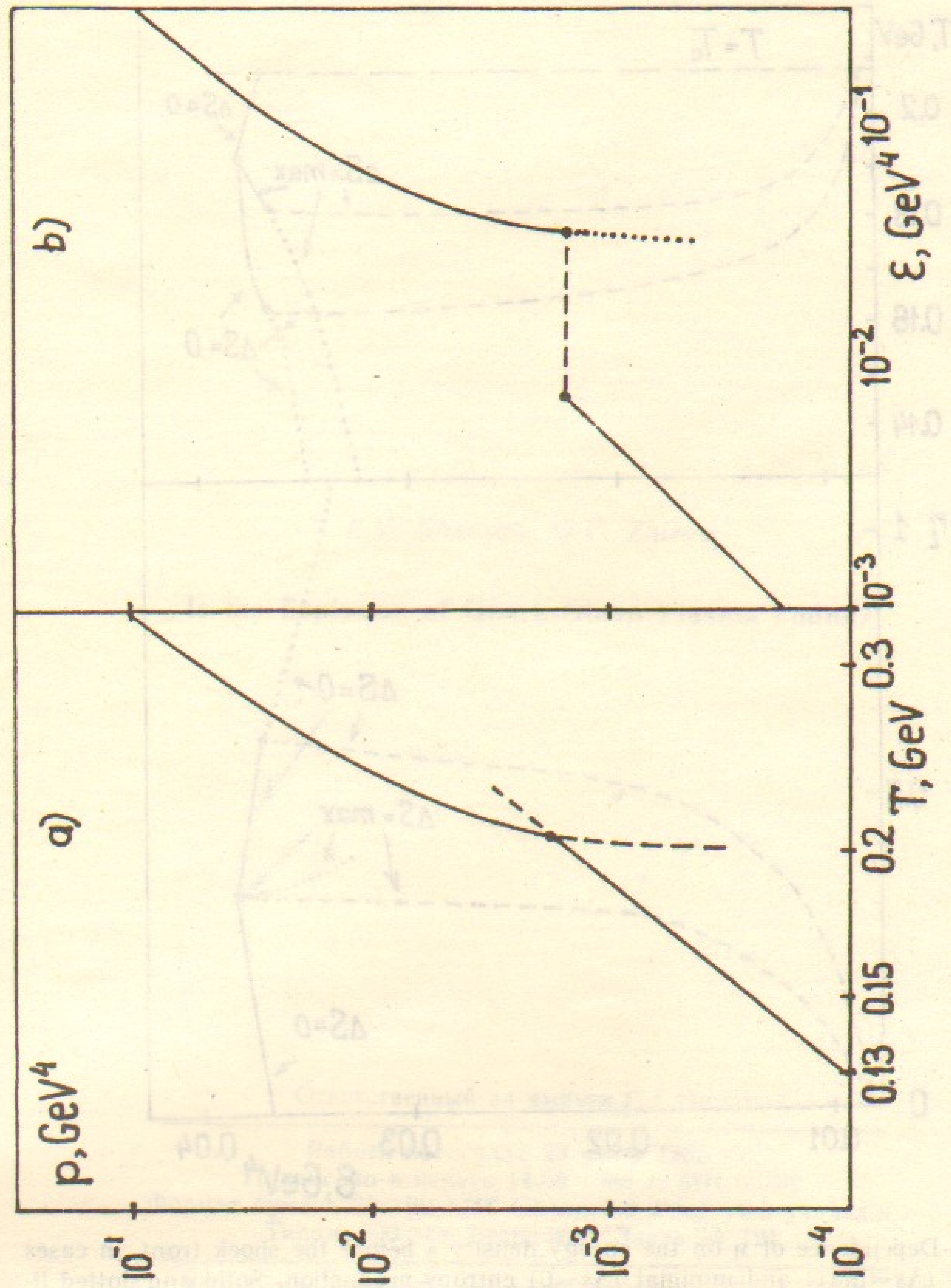

Fig. 2. Pressure p versus temperature T (a) and versus energy density ε (b). Dotted line illustrates supercooled quark-gluon phase, while dashed one corresponds to mixed phase.

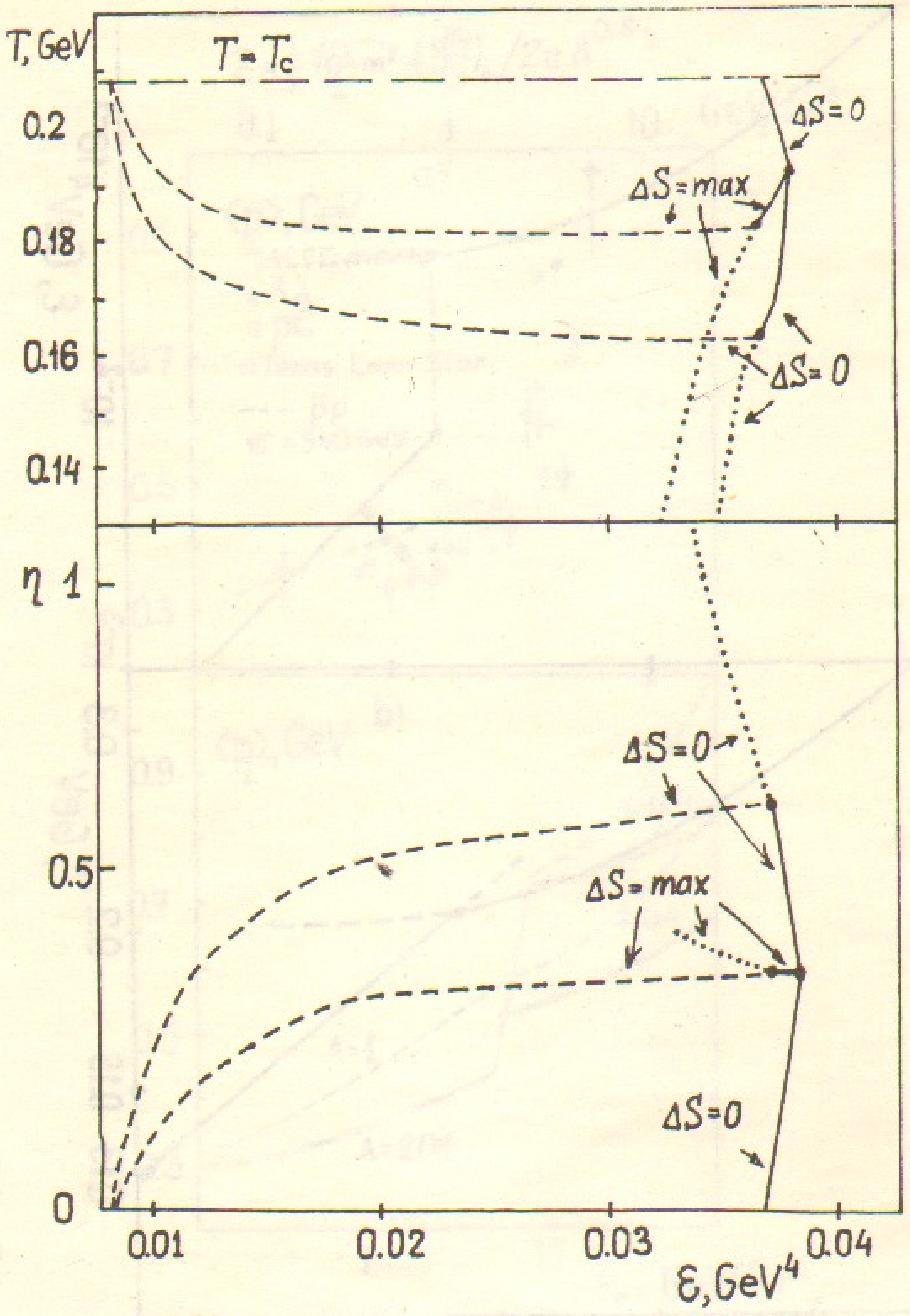

Fig. 3. a —Dependence of η on the energy density ε before the shock front, in cases of maximal ($\Delta s = \max$) and minimal ($\Delta s = 0$) entropy production. Solid and dotted lines correspond to jump from normal and supercooled quark-gluon phases, respectively, while dashed ones correspond to jump from the mixed phase. *b*—Corresponding temperature of hadronic phase after the shock front.

E.V. Shuryak, O.V. Zhirov

Is the Explosion of Quark-Gluon Plasma Found?

Ответственный за выпуск С.Г.Попов

Работа поступила 23 июля 1985 г.
Подписано в печать 14.08 1985 г. МН 06702
Формат бумаги 60×90 1/16 Объем 0.9 печ.л., 0.8 уч.-изд.л.
Тираж 290 экз. Бесплатно. Заказ № 121

Набрано в автоматизированной системе на базе фото-наборного автомата ФА1000 и ЭВМ «Электроника» и отпечатано на ротапринте Института ядерной физики СО АН СССР,
Новосибирск, 630090, пр. академика Лаврентьева, 11.