Работа поступила - 7 марта I980 г.

Ответственный за выпуск - С.Г.ПОПОВ
Подписано к печати - I2.Ш-I980г. МН 06658
Усл. 0,9 печ.л., 0,8 учетно-изд.л.
Тираж 200 экз. Бесплатно
Заказ № 92.

Отпечатано на ротапринте ИЯФ СО АН СССР

СИБИРСКОЕ ОТДЕЛЕНИЕ АН СССР
ИНСТИТУТ ЯДЕРНОЙ ФИЗИКИ

E.V.Shuryak

PRODUCTION OF QUARK-GLUON PLASMA IN HEAVY ION COLLISIONS AND HOW TO LOOK AT IT

ПРЕПРИНТ 80-92

Новосибирск

Production of quark-gluon plasma in heavy ion collisions and how to look at it

E.V.Shuryak

(Based on the talk given at
International conference on extreme states of
nuclear systems, Dresden, DDR, february 1980)

Abstract

Theoretical status of the phase transition from normal matter to quark-gluon plasma is reviewed. The estimated critical parameters are compared with those reachable in heavy ion collisions with the conclusion that first consequences of such transition may be found at energies 5-10 Gev per nucleon. Some propositions about data analysis are made, based on the similar anlysis of pp data at much higher energies, in which some indication on such transition are found. At the end some speculations are given concerning the possible measurements of "vacuum pressure", the very fundamental quantity of QCD.

Introduction

In the present paper I discuss the following questions:

1. What we know about critical conditions at which the usual matter undergoes transition to the new phase, the quark-gluon plasma.
2. What is the physics of this transition and to what extent it is connected with quark confinement.
3. To what extent the matter is compressed and excited in the collision of given energy.
4. How the matter is cooled down in the expansion and when it breaks into physical secondaries.
5. What are the experimentally observable consequences of the production of some fireball of quark-gluon plasma.
6. What kind of fundamental information can be found in such investigations.

Quite clear, I am not able to give exhaustive answers to these questions, covering the whole fields of high energy physics which do not so far exist. However, trying to give such answers is the best way to explain the present status of our understanding. In the rest of the introduction the main ideas and sources of information are enumerated and briefly discussed, while in the other sections we do it in more details.

In order to answer the first question one has to know the thermodynamical potentials for both phases of matter. For normal matter we have various calculations in gas approximation for hadrons (pions, nucleons etc.). For quark matter we have calculations |1| made in the framework of perturbation theory in QCD coupling constant α_s . Both approaches are not applicable in the transition region, but their extrapolation can probably give the right idea about the transition parameters.

The second question is more difficult because one should account for nonperturbative QCD effects. At the moment there are two different branches of this theory. One of them deals with instantons, the nonlinear fluctuations of vacuum gauge fields. The other one tries to demonstrate quark confinement using the analogy with some lattice gauge models. The theoretical review of them is given in [2] .

The questions 3 and 4 we try to answer in the framework of the macroscopic approach, in which the matter excitation is made in the shock wave and the expansion process is assumed to be quasi adiabatic. The real nuclei are not macroscopic objects, so strong corrections may appear. At the moment only qualitative discussion of their effect may be given.

The question 5 is the most difficult one. Indeed, the fireball of excited matter is very unstable object and, when created, it very soon cools down and decay. Some experience we have in the analysis of proton-proton collisions shows that global features of the collision like total multiplicity, angular distribution etc. are not very useful in this framework. One should better look at some "tails" of spectra, connected with direct emission from hot fireball during its lifetime. Some examples of the type are given, based on papers [10-12].

As for the last question, one may say that only time will show what fundamental information can be found on this way.

Still I would like to make some speculations concerning the determination of the so called "vacuum pressure" acting on the quark-gluon matter. If this program [12] turns out realistic in some future, it surely be a good answer to this question.

Phase diagram

Let me begin with the discussion of a question which has been asked for many times: why we speak about phase transition to quark-gluon plasma and do not imagine some continous transition, say similar to ionisation of atoms ?

As far as we understand it now, the high temperature limits in both cases are similar indeed. At the same time there is qualitative difference in the low temperature phase: quarks are confined and electrons are not. So, from very general arguments we await qualitative changes in the system, or the phase transition.

People often use analogy in such discussion with more familiar cases like superconductivity. Really, superconductor expells the magnetic field like (presumably) QCD vacuum expels color fields. Also both phenomena are absent at high temperature, see more in [3] . But, we still can not find the simple analog to Cooper pair wave function, the so called order parameter which is zero in one phase and nonzero in another. The confinement criterion as suggested by Wilson looks rather different and many people are now working on reformulation of QCD in order to meet somehow both lanquages.

Another direction is the explicite account for instantons, the particular fluctuations of gauge fields in vacuum due to tunneling between different field configurations with zero classical energy. They have been discovered by Polyakov and collaborators, and now we know that although they do not produce confinement by themselves, they act in the right direction and produce large and interesting effects.

In order to explane their role in the transition in question let us note the following important fact: the possibility of tunneling usually lower the ground state energy, and instanton-like fluctuations are not an excaption. Due to very important analysis [4] we know today even the numerical value of the vacuum energy density connected with nonperturbative effects: $\varepsilon_0 \simeq -$ 450 Mev/fermi^3. So, instantons (like pairing in superconductors) is energetically favourable phenomenon.

Now, it has been found that in very dense and/or excited matter [5] and strong color field [6] the instantons are suppressed. As a result, these forms of matter are under constant pressure acting from vacuum and equal to $p_0 = -\varepsilon_0$. So, we have derived the so called MIT bag model [7], which uses exectly the same way of balancing the quark pressure on the boundaries of hadrons. To be more specific, the first order transitions are found. Note however, that such type of transition is not needed from any general considerations, and it appears only in explicit calculations with accuracy which is not yet understood good enough. The physics of this transition is that at some density of matter it becomes unstable according to decay into inhomogeneous phase, in which matter clusters are surrounded by vacuum.

Such instability seems to take place at zero temperature [5], but it is not yet clear what happens at nonzero one. The Fig.1 demonstrates the two possible behaviour of the phase diagram. The solid lines show the critical parameters for the first order transition. They surround the unstable region (dashed at the figure). The dashed line is the possible second order transition, and the dotted line separate the region where the pion condensate is predicted.

Let us warn the reader that this phase diagram is based on calculations which are somehow preliminary in sense that much more studies are needed before we actually understand their accuracy. At present we only hope to make good first approximation.

Matter excitation and cooling in the collisions

Now we concentrate on questions 3 and 4 from our list. The answers to them may be summarized in form of some trajectory which the excited matter makes on the phase diagram discussed above. Such trajectory is shown at Fig.2.

The upgoing solid curve corresponds to the so called shock adiabate which in the relativistic case looks as

$$w_0^2 \cdot n^2 - w^2 \cdot n_0^2 = (p_0 - p)(w \cdot n_0^2 + w_0 \cdot n^2); \quad w = \varepsilon + p$$

where ε, n, p are the energy density, barion charge density and pressure, and those with the index "o" correspond to initial values of the parameters. At given energy of the collision per nucleon in the center of mass E the compression is equal to

$$n = n_o \left(\frac{1 + c^2}{c^2}\right) \cdot \frac{E}{m}$$

where $c^2 = dp/d\varepsilon$ and m is the nucleon mass. The last factor is the Lorentz compression, and the second one is the compression in the shoch wave. Of course, these relations are valid only in the macroscopic limit, or for collisions of two very large pieces of matter. At the same time let us note, that these results are based at very general considerations, namely the conservation of energy, momentum and barionic charge.

The dashed curves going down at Fig.2 are those corresponding to matter cooling in the expansion process. In the idealized macroscopic limit such expansion is quasi adiabatic and the corresponding curves are determined by the condition that matter and entropy density decrease in the same way: $n_B \sim s \sim T^{1/c^2}$.

Whatever large is the initial system, at some time moment the applicability condition for the use of the macroscopic approach L >> l (where L is the system dimensions, and l is the mean free path) is violated, for ℓ grows with system expansion. As it was first noted long ago by Pomeranchuck [8] this very moment determins the temperature energy spead of the secondaries. This moment of break-up, shown by cross at Fig.2, corresponds to the so called final temperature T_f.

Now, to what extent these results are changed if one discusses the finite systems with not very large L/l ? The first such effect is that quarks are more penetrable than gluons, so at large energies they more easily "go through" the target. We know this to take place in pp collisions, where the so called leading protons are well seen. This effect essentially reduce the reachable density and move the curves of Fig. 2 to the left.

The second effect is that the matter excitation needs time, so for finite systems the transition from the one curve to another will be somehow more round. This comment may be compared with the "experimental" value of the initial temperature T_i to be discussed below. Important, that it is a little below the theoretical point.

Some idea about the role of such effects may be obtained from cascade calculations, say [15] . Of course, such calculations ignore the collective phenomena like phase transitions we are looking for, so they are used just as an example. These calculations show, that there is also significant energy loss due to "evaporation" of more energetic particles and the trajectory looks rather differently for finite systems.

So, a lot remains to be understood here, including the viscosity and heat transport in superdense matter. Anyway, we are able to say, that at least at laboratory energy of 5-10 Gev per nucleon we really produce some fireball of quark gluon plasma. In the macroscopically large colliding systems the needed energy is smaller, 1-2 Gev per nucleon [9] , but available nuclei are in fact not so large.

Observable consequences of the quark plasma production

Collisions of heavy nuclei is rather complicated phenomenon, for its understanding a lot of work, both experimental and theoretical is needed, so it is very difficult to predict what particular parameters will become more important in future analysis. In this section I discuss briefly what is already found by our group from the available data on proton-proton collisions at very high energies. These observations can be considered as indications to qualitative validity of the macroscopic approach up to ISR energies for proton-proton collisions. However, the similar analysis of the future nuclei-nuclei data is crucial for real understanding of its accuracy.

Now, let us assume that this language is correct and that the system in question really goes along the trajectory in the phase plane discussed in the preceeding section. How this trajectory is connected with the observed spectra of secondaries ?

In the true macroscopic limit the answer is uninteresting: the spectrum of secondary hadrons is determined by the conditions in the final break-up point, shown at Fig. 2 by crosses.

However, there are some exceptions. First, it is the production of photons and leptons for they are not closed by interation in the system and go out freely. Second, it is the production of charmed particles. The rate of their recombination is very small due to low density, so they surely cannot be in equilibrium with other matter during the expansion and their observed output is connected with hot initial part of the trajectory, not with the cool break-up stage. Both effects are estimated in [10] .

Also one should include the surface leakage of particles, which takes place during all the expansion process. Of course, this is $O(L^{-1})$ effect (L is the system dimension), but still it may be seen for large particle masses and/or transverse momenta where the main effect is suppressed by the Boltsman factor with small break-up temperature T_f. These surface evaporation phenomena we are going to discuss below.

Fig. 3 shows the schematic devision of the spectrum of secondary pions, produced in pp collisions, into several regions in which different production processes dominate. The data points are not shown, but the quality of the fit is good enaugh. So, going from small to large p_t one comes across the following phenomena: final break-up, evaporation of hadrons, evaporation of quarks with subsequent fragmentation into hadrons and finally the so called hard collisions of quarks and qluons which are well described by the parton model and QCD lowest order diagrams. How one is able to separate them all ?

The straitforward theoretical way is the direct calculation of the spectra and comparison with data. This is done for evaporation processes in [10,11] . However, each region has its own level of understanding, and purely quantitative approach is not very convincing.

Another approach is to look for some qualitative changes in data while one comes from one region to another, or in other terms, taking the derivatives of the data. An example of this kind [11] is shown at Fig. 4 , it corresponds to p_t dependence of the slope of the p_t distribution of pions at Batavia and ISR energies. One may see that this dependence is not flat and has "step-like" structures. Such structures are in very good agreement with theoretical ideas discussed in the preceeding section since the trajectory in the phase plane has singular points as well. The most evident ones are the initial and final temperatures T_i and T_f , but one may also look for that due to phase transition to quark plasma T_c. Estimates we made shows that in pp collisions even for Batavia energies T_i is not larger than T_c, and therefore one should see only two steps. At ISR energies one may see three, but data are not so far good enough. Additional important information is obtained in 11 by taking the derivative of energy dependence of spectra, but we have no place here to discuss it.

Another simple example of such qualitative analysis is the studies of ratios of production rate for various secondaries. It is of particular interest for the transition from hadronic gas to quark plasma, for these ratios depend strongly on what kind of object is really evaporated from the system, the hadron or the quark. Say, for for barion to meson ratio one may think that it is of the order of unity after the Boltsman factor is extracted or if one take the same transverse mass $M_t = (m^2+p_t^2)^{1/2}$.

In fragmentation of quarks, as we know from e^+e^- to hadrons, it is much smaller. The data show rapid fall of this ratio at M_t around 2 Gev. The corresponding slope in this region is near 250 Mev, close to the predicted T_c value.

Concluding our discussion about pp data analysis we may say, that both qualitative analysis and model dependent calculations agree that for energies higher than 100 Gev some fireball of quark plasma, being in approximate local thermal equilibrium, is really produced. The collisions of heavy nuclei can do more in this field, and we hope that similar analysis of future data will be useful. Note once more, that in this case so high energies are not needed.

Looking for fundamental information

At the end of this talk I would like to discuss some speculations [12] about the possible connections of heavy ion collisions with more fundamental physics. As we have discussed in the beginning, the quark plasma is relatively simple state of matter, similar to ideal gas. In contrast to this, the normal state of matter and even the physical vacuum turns out to be very complicated, filled by strong and poorely understood fluctuations of the gauge fields. "Melting" them experimentally in ion collisions we find how strong they are.

Being more spesific, the vacuum pressure on quark plasma is important during the expansion process, for it acts against such expansion. If no transition to separate hadrons takes place, the expansion of excited matter is finally stopped and some large bag is formed, the whole kinetic energy being spent to "vacuum melting". In reality the system breaks into clusters at the same moment, but still the hydrodynamical process is affected. As estimates shows, this effect may reduce the collective expansion velocity very strongly. As discussed in [12] in more details, this is just in agreement with data on low p_t spectra of various secondaries in pp collisions. These spectra are with very good accuracy thermal, and this was a little bit puzzling for no trace of collective motion was seen.

Note, that the "true" vacuum pressure is predicted to be one order of magnitude larger than the bag constant found in the fit of the bag model. This difference is, after all, connected with the fact that usual light hadrons are far from being macroscopically large.

So, we conclude, that the careful analysis of the hydrodynamical collective velocity in the expansion of quark plasma into physical vacuum may give us the very important information, the energy density of vacuum QCD fluctuations.

References

1. B.A.Freedman, L.D.McLerran. Phys.Rev. D16 (1977) 1130, 1147, 1169. E.V.Shuryak. Zh.E.T.F. (Sov. Phys. JETP) 74 (1978) 408. V.Baluni. Phys.Rev. D17 (1978) 2092.
2. E.V.Shuryak. QCD and the theory of superdense matter. Phys.Reports, in press.
3. A.M.Polyakov. Phys.Lett. 72B (1978) 477. L.Susskind. Phys.Rev. D20 (1979) 2610.
4. A.I.Vainshtein, V.I.Zakharov, **M.A.Shifman. Nucl.Phys.** B147 (1979) 385,448, 519.
5. E.V.Shuryak. Phys.Lett. 79B (1978) 135, 81B (1979) 65.
6. G.Callan, R.Dashen, D.J.**Gross. Phys.Lett. 78B** (1978) 307, Phys.Rev. D17 (1978) 2092.
7. **A.Chodos, R.L.Jaffe, K.Johnson, C.B.Thorn, V.F.Weisskopf.** Phys.Rev. D9 (1974) 3471.
8. I.Ya.Pomeranchuck. **Doklady Akademii Nauk SSSR** 78 (1951) 889.
9. S.A.Chin. Phys.Lett. 78B (1978) 522.
10. E.V.Shuryak. Phys.Lett. 78B (1978) 150.
11. O.V.Zhirov. Jadernaja **fisika (Sov.J. of Nucl. Phys.)** 30 (1979) 1098. **On the applicability limits of parton and hydrodynamical describtion of hadronic collisions", preprint 79-114, Novosibirsk Inst. of Nucl.Phys.**
12. O.V.Zhirov, **E.V.Shuryak. Phys.Lett. 89B (1979)** 253.
13. D.C.Cavey et al. Phys.Rev. D14 (1976) 1196.
14. K.Eggert et al. Nucl. Phys. B98 (1975) 49.
15. K.K.Gudima, V.D.Toneev. **Extreme conditions reachable in high energy heavy ion collisions. Dubna preprint E2-12624,** 1979.

Figure captions

1. Phase diagram of matter at high barion number density n_B (in units of that for nuclear matter n_o) and high temperature T (Mev). Figures a and b give two possiblities, depending on the structure of unstable region (dashed). Solid lines correspond to phase order transition to quark plasma, the dashed ones - possible second order transition, and the dotted line separate the region in which pion condensate is predicted.

2. Trajectories on the phase plane made by the system during the heavy ion collisions. The upgoing curve is the shock adiabate, the dashed ones are the usual adiabates and they correspond to expansion. Two energies per nucleon are shown, 6 and 800 Gev. The former for heavy ions, and the latter for our discussion of high energy pp data. Arrows shows "experimental" initial temperature as shown at Fig.4.

3. Schematic presentation of the regions in the spectrum of pions, produced at zero rapidity at $(S)^{1/2} = 53$ Gev. Data points are not shown, but correspond to the curve. Mechanisms of pion production in all these regions are given at the Figure.

4. The slope of spectra $T_{eff} = (d\ln(d\sigma/dp_t^2 dy)/dp_t)^{-1}$ in Gev versus transverse momentum p_t. The upper curves and data are at $(S)^{1/2} = 20$ Gev, the lower at 44 Gev. Closed points are [14], and open ones are [13]. The lines are schematic theoretical predictions of "steps", corresponding to some singular values of temperature.

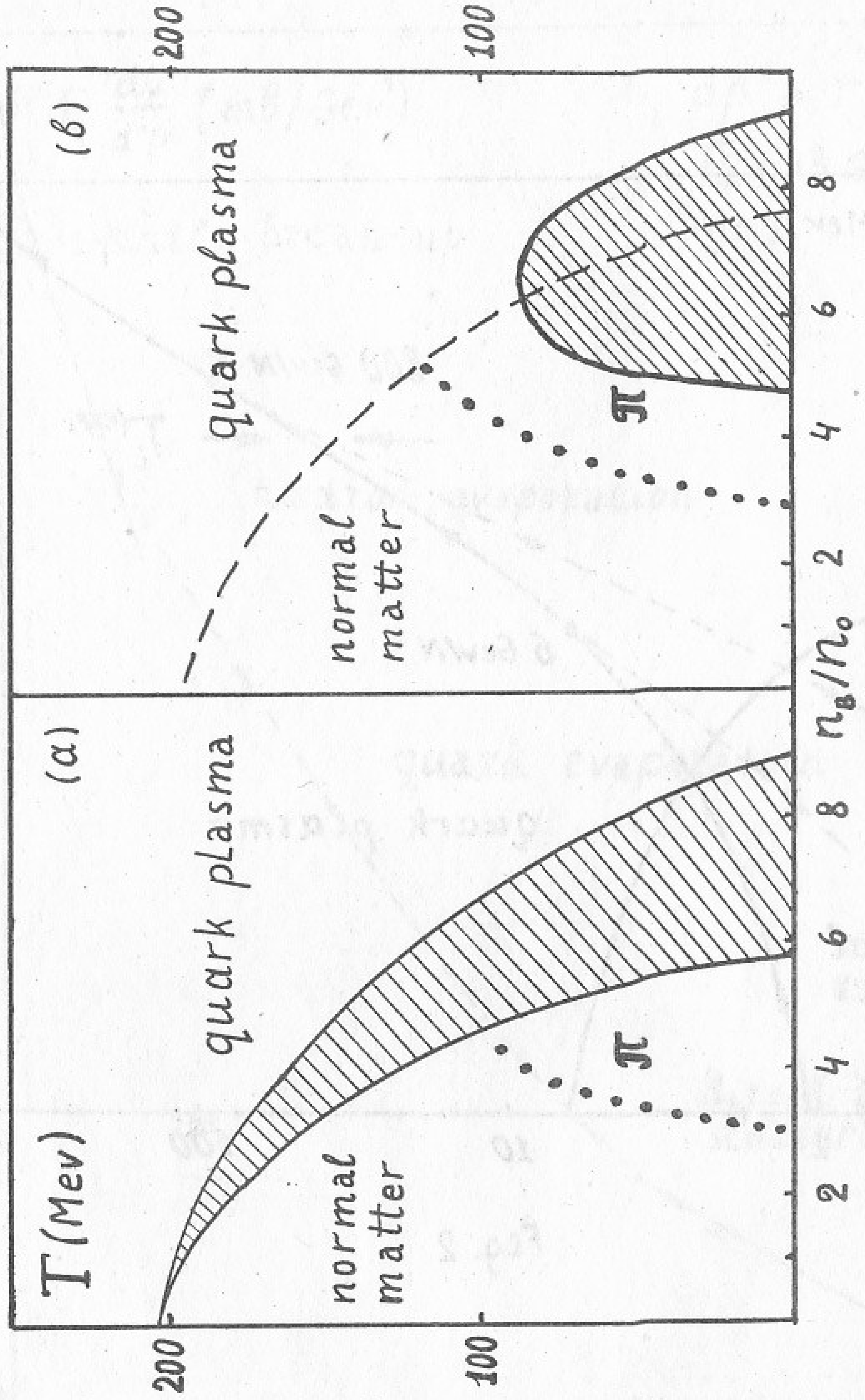
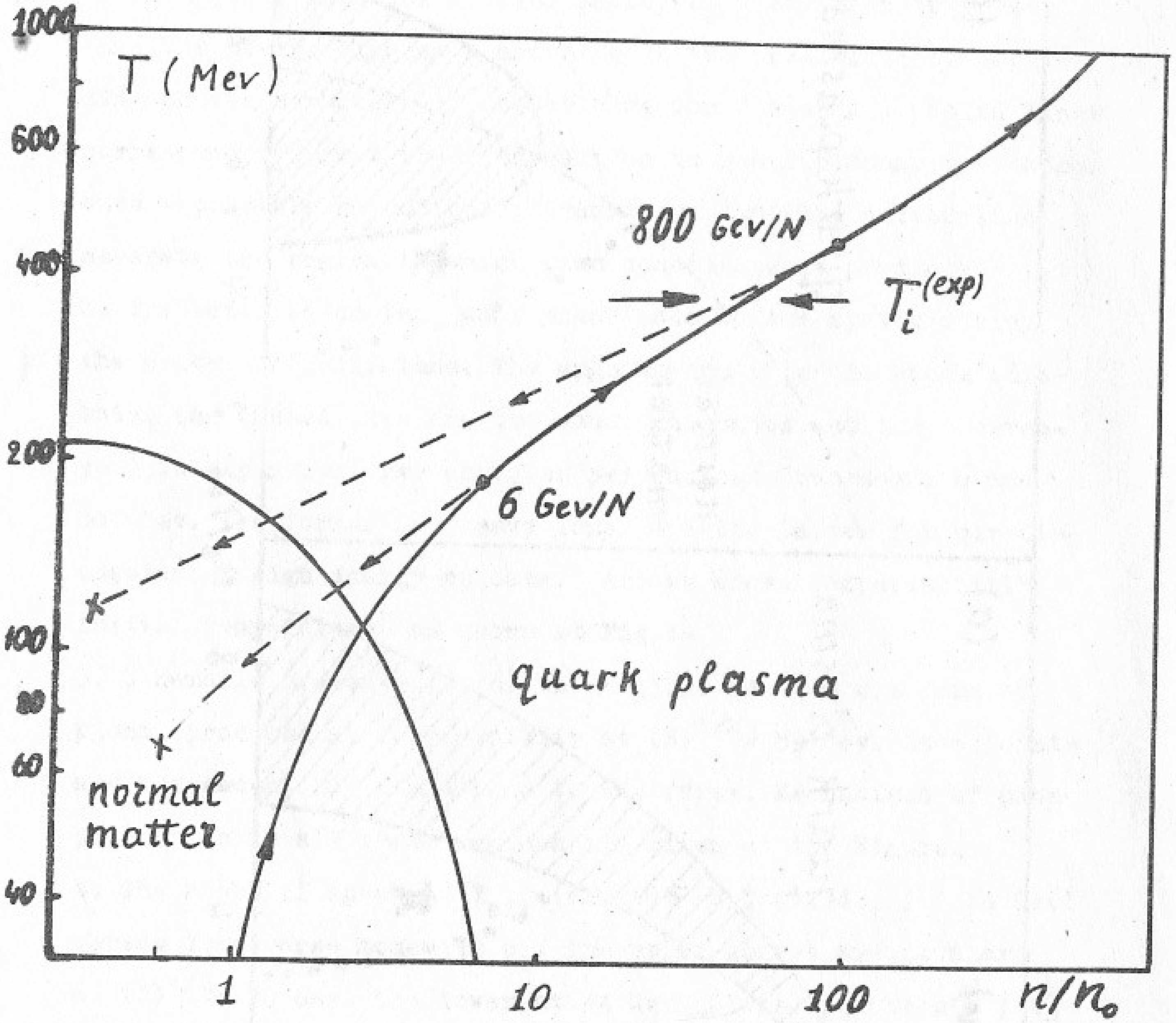
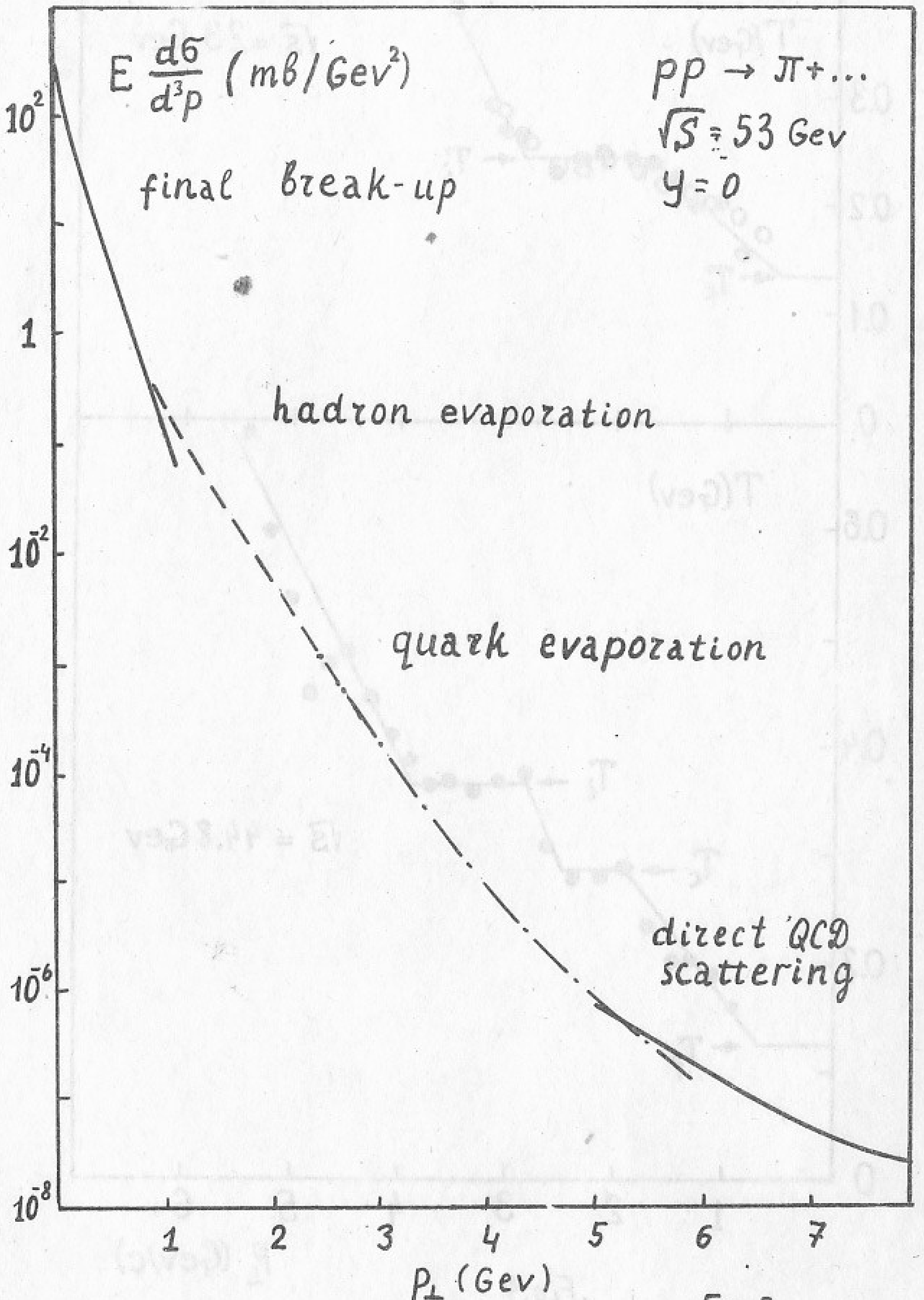


Fig. 1



T (Mev)
1000
600
400
200
100
80
60
40
800 Gev/N
$T_i^{(exp)}$
6 Gev/N
quark plasma
normal matter
1
10
100
n/n_0

Fig. 2



$E\frac{d\sigma}{d^3p}$ (mb/Gev^2)
$pp \to \pi + \ldots$
$\sqrt{s} = 53$ Gev
$y = 0$
final break-up
hadron evaporation
quark evaporation
direct QCD scattering
10^2
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
1
2
3
4
5
6
7
$P_\perp$ (Gev)

Fig. 3

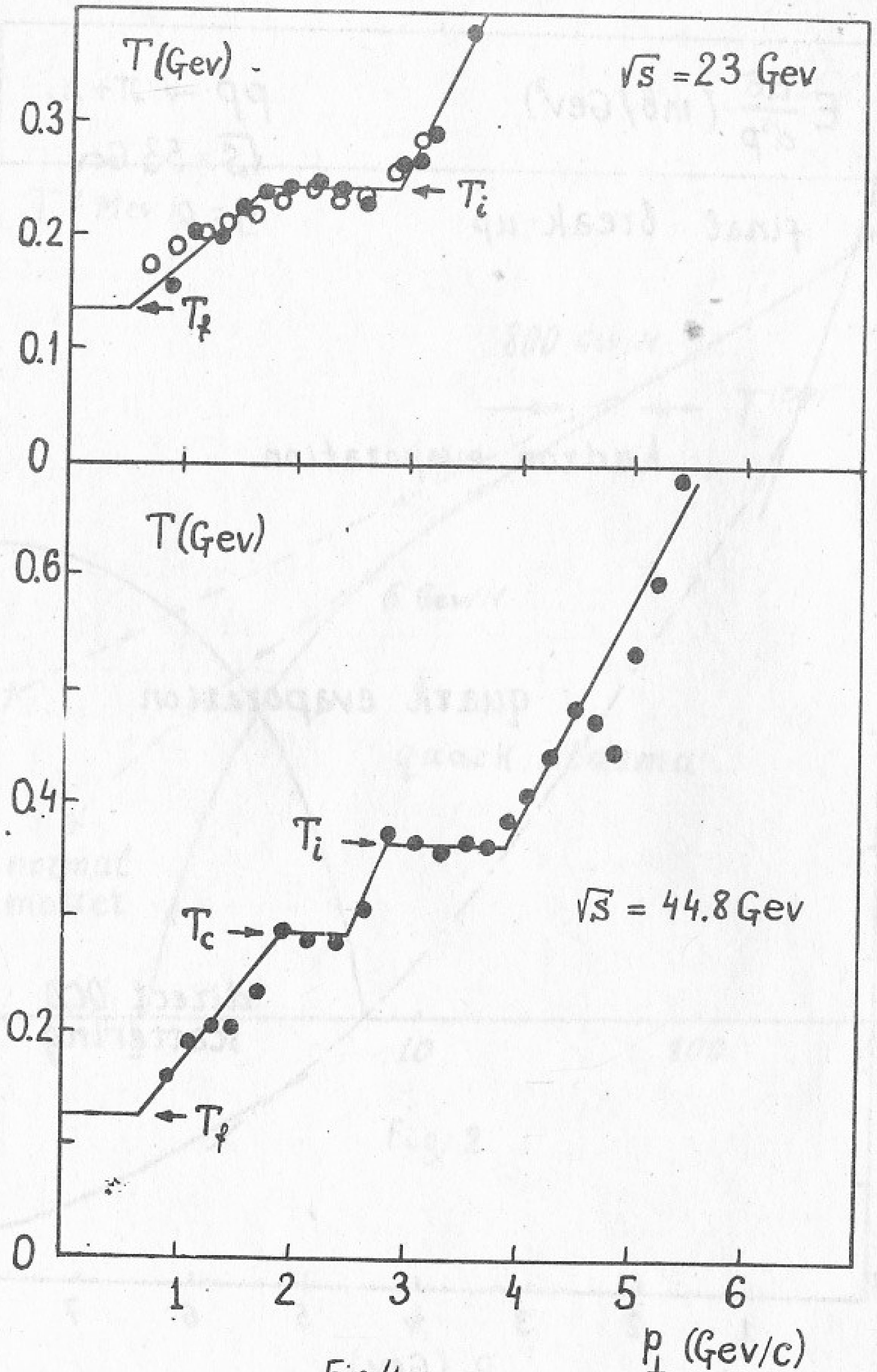

T(Gev)
√s = 23 Gev
0.3
0.2
0.1
0
T_i
T_f
T(Gev)
0.6
0.4
0.2
0
T_i
T_c
T_f
√s = 44.8 Gev
1
2
3
4
5
6
p⊥ (Gev/c)

Fig.4