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H.W.Barz, B.Kämpfer

TWO-FLUID MODEL WITH ENERGY LEAK-OUT APPLIED TO ASYMMETRIC ULTRA-RELATIVISTIC HEAVY-ION COLLISION

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1. Introduction

The current CERN experiments of bombarding various target nuclei with ^{16}O and ^{32}S ions at 60 and 200 GeV·A are a unique challenge to test different models developed for ultra-relativistic heavy-ion collisions and to look for possible signals of the deconfinement transition. The recent analysis /1,2/ of the proton-nucleus data at 100 and 200 GeV leads one to the conclusion that nuclear matter of a thickness of 12 fm reduces the rapidity of an incident proton by 2 - 2.4 units. This sets an upper limit of about 50 GeV at which ions might be stopped by heavy target nuclei. So at CERN energies we expect that nuclei transverse, at least partially, one another. This picture is supported by the increase of the transverse energy as a function of the target mass (e.g. see /3/).

The first inclusive data are fairly well reproduced by models relying on the superposition of independent hadron-hadron collisions /4/. This seems to point to the nonappearance of collective degrees of freedom. Otherwise, it would be very surprising if any collectivity in large nuclei would be absent. Such collective effects are a necessary condition for deconfinement and excitation of the quark-gluon plasma. Parallel to the experimental search for collectivity one should therefore elaborate models which include properly those effects, one is looking for, such as deconfinement. The question of a possible phase transition can best be considered within the framework of hydrodynamics. Hydrodynamical investigations without assuming a phase transition were already done within the one-fluid model /5/. There it was assumed an instant stopping and a fast achievement of local equilibrium of nuclear matter. This assumption is certainly rather crude. To maintain the usefulness of fluid-dynamical approaches one can use multi-component fluid models. These allow one to replace the too strong assumption of instant stopping and equilibration between target and projectile matter by assuming a finite momentum degradation length and only local equilibrium within each fluid component separately.

Here we apply a two-fluid model, where projectile and target are considered as two distinguishable fluids /6-9/. These two fluids interact with one another by exchanging momentum and energy but no baryons. In the models used until now conservation of the total energy is assumed. Here we extend the two-fluid model to take into account that a certain amount of energy is deposited into the midrapidity region. Because we are mainly interested in the baryon-reach fragmentation region we treat this effect by introducing an energy loss term in the equations of motion and do not consider explicitly the evolution of the midrapidity region. Our present aim is to obtain a space--time picture for the collision process, to calculate the rapidity distribution of hadrons in longitudinal direction and to estimate the maximum temperatures for different deconfinement time scales.

2. Basic ingredients of the model

Both colliding nuclei are simulated by two perfect fluids each one described by an energy-momentum tensor

$$T^{ij} = (e+p)\,u^i u^j + p\,g^{ij}, \qquad (1)$$

where u^i is the four velocity, while p and e denote the pressure and the energy density. To describe the phase transition the fluid is assumed to consist of a mixture of a hadronic and a quark-gluon phase. The quantities e and p are given as functions of the baryon number density n and the temperature T. For hadronic matter we use a quadratic approximation for the compression energy per particle with an incompressibility coefficient of 280 MeV and the thermal energy of Boltzmann gas. The quark matter is modeled by a gas of light quarks and gluons. These equations imply a phase transition of first order (for details see ref. /9/) which reflect important features of the matter expected from QCD arguments.

Further we assume a finite transformation time for the phase transition. The transformation rate is controlled by a relaxation time τ via

$$\dot{x} = -\frac{x - x_{eq}}{\tau}, \qquad (2)$$

where x denotes the fraction of the hadronic phase in the matter and x_{eq} is the equilibrium density for a given temperature and density. The value of τ should be related to the QCD confinement energy scale and is estimated to be in the order of 1 fm/c based on the value of the bag constant. We shall check the influence of the velocity of the phase transition by carrying out calculations varying τ from 0.1 fm/c to 10 fm/c simulating the effects of a sudden and of a hindered phase transition, respectively.

The equation of motions of both the fluids are coupled locally according to

$$T^{ij}{}_{,j} = -Dn\bar{n}(u^i - \bar{u}^i) - q\bar{n}u^i, \quad (nu^i)_{,i} = 0, \qquad (3a)$$

$$\bar{T}^{ij}{}_{,j} = -Dn\bar{n}(\bar{u}^i - u^i) - qn\bar{u}^i, \quad (\bar{n}\bar{u}^i)_{,i} = 0, \qquad (3b)$$

where (un)barred quantities refer to the target (projectile) fluid. The diffusion term proportional to D has already been used in the analysis of nucleus-nucleus collisions in the GeV region (see /6-8/). The term proportional to q goes beyond the traditional two-fluid model. It takes into account the energy drain into the midrapidity region, where colour strings are formed which materialise later. We assume that the energy loss is proportional to the thermal excitation energy of the fluid $q = Q(e - e_c)/n_o$ as long as the rapidity difference of both fluid elements is larger than $\Delta y = 2$, where e_c is the cold compression energy density of the matter. Basing on the relativistic transport theory, equations of motion with the same structure as eqs. (3) have been derived in ref. /10/; there the drain term is associated with inelastic scattering processes.

3. Proton stopping

To get an idea of the meaning of the parameters D and Q we model the motion of a point-like particle in nuclear matter of saturation density n_o by using eqs. (3a). Then, introducing $m^* = e/n$ and discarding all terms connected with the pressure of the projectile to hinder its expansion, eqs. (3a) are transformed into coupled differential equations for the projectile with rapidity y and excitation energy m^*:

$$\frac{dy}{dz} = -\frac{Dn_o}{m^*}, \quad \frac{dm^*}{dz} = -Q\,\frac{m^* - m}{\operatorname{sh} y} + Dn_o\,\frac{\operatorname{ch} y - 1}{\operatorname{sh} y}, \qquad (4)$$

where m denotes the nucleon mass. We solve these equations for a target having a thickness of z_t = 12 fm. In fig. 1 we show which values of the parameters D and Q are needed for obtaining a certain rapidity loss of the projectile. To obtain a rapidity loss of $\Delta y = 2.2$ as anticipated in ref. /2/ the diffusion constant has to lie in the range of D=(3 - 3.5 GeV fm^2). An increase of the strength of the drain enhances the rapidity loss because the effective mass of the fluid elements becomes smaller. The values of D obtained here are considerably larger than that obtained from the analysis of proton--proton data which give a rapidity loss of 1.3 units for the projectile /9/. On the other hand ref. /7/ proposes a considerable larger value. For $Q = 0$ the projectile becomes strongly excited up to values of 12 m. A finite value of Q reduces this excitation strongly. In what follows we use in our hydrodynamical calculations D= 3 GeV·fm^2 and Q = 2 fm^{-1} as representative values.

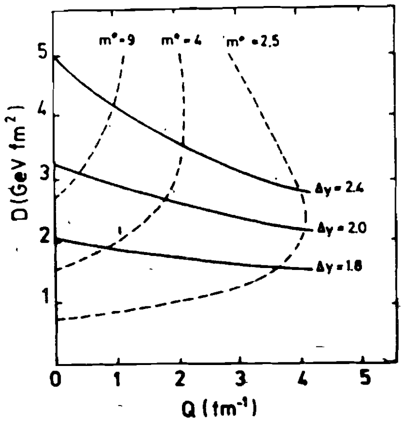

Fig. 1. Values of the model parameters D and Q needed to rea ch the rapidity losses Δy = 1.6, 2.0 and 2.4 of a projectile with incident energy of 100 GeV after transversing 12 fm nuclear matter according to eqs. (4) (heavy lines). The dashed lines connect equal effective mass values.

4. Calculations in slab geometry

Our investigations are carried out within the one-dimensional hydrodynamical model. We maintain the simplicity of the model in

order to investigate the importance of a non-equilibrium transition to quark-gluon plasma. (Three dimensional investigations have shown that one-dimensional calculations describe reliably the central part in head-on collisions.) In simulating the ^{16}O experiments at CERN we choose a projectile slab having a thickness of 4.9 fm and vary the thickness of the target slab. The distribution of the matter is calculated as a function of the rapidity. This distribution should essentially correspond to the baryon distribution in experiment while the pion distribution cannot be calculated within our model because we do not follow explicitly the formation of the midrapidity region. In fig. 2 we represent the resulting baryonic distributions obtained for $Q = 0$ and two characteristic values of the diffusion coefficient D for the collision with a heavy target ($z \approx$ 12.1 fm) at E/A = 60 GeV bombarding energy. For the small value of D= 1 GeV fm^2 the projectile baryons remain concentrated in a single rapidity peak.

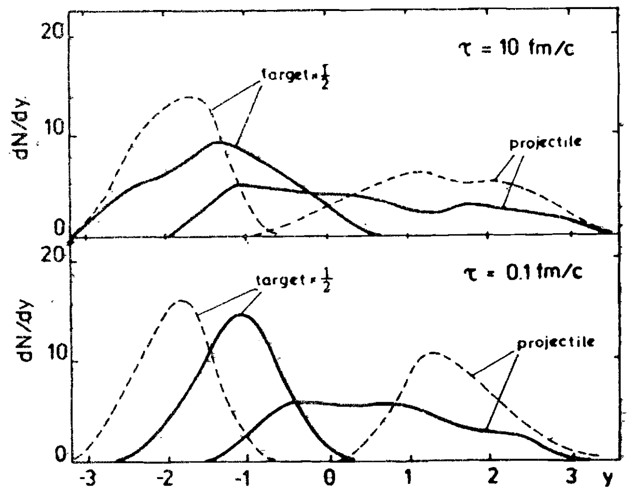

Fig. 2. Baryon multiplicities of target and projectile as a function of rapidity for a slab of 5 fm thickness traversing a target slab of 12 fm thickness for 60 GeV·A bombarding energy. The dashed (solid) curves are calculated with a diffusion coefficient of D=1 (3) GeV·fm^2 and $Q = 0$ for a slow (upper part) and a fast (lower part) phase transition.

With increasing coupling the projectile baryons become spread over a wide region which extends into the target region. Eventually a double--humped distribution appears, reflecting the fact that one part penetrates while the other one tends to stick in the target matter. This effect is more pronounced for a hindered phase transition (τ = 10 fm/c), where the matter consists dominantely of the hadronic phase the higher pressure of which leads to a stronger expansion. The space--time picture is verified by the world lines of the baryons shown in fig.3. One observes that the projectile explodes within the target.

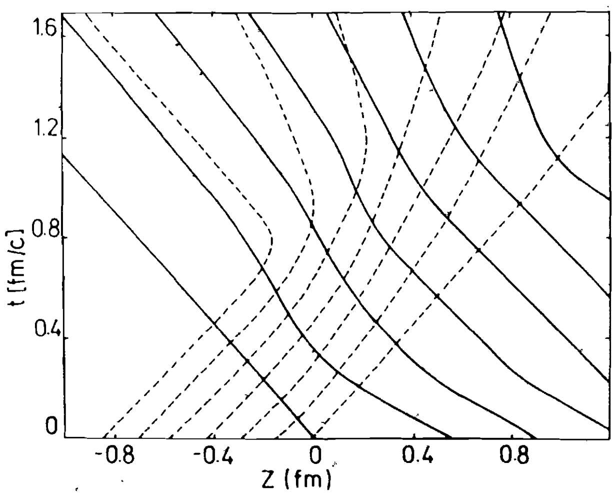

Fig. 3. World lines of a 12 fm thick target (heavy lines) and a 4.9 fm thick projectile baryons (dashed lines) as seen in the equal velocity frame for the following set of parameters: E= 60 GeV·A, D= 3GeV fm^2, Q= 2 fm^{-1}, τ = 10 fm/c.

In this case of strongly overlapping distributions the colour strings would materialise within the hadronic matter; and the drain term scheme is not longer useful.

For the anticipated values of D = 3 GeV fm^2 and Q = 2 fm^{-1} target and projectile distributions overlap strongly and can hardly be separated experimentally. In fig. 4 the total multiplicity distributions for a bombarding energy of 200 GeV are represented. The main

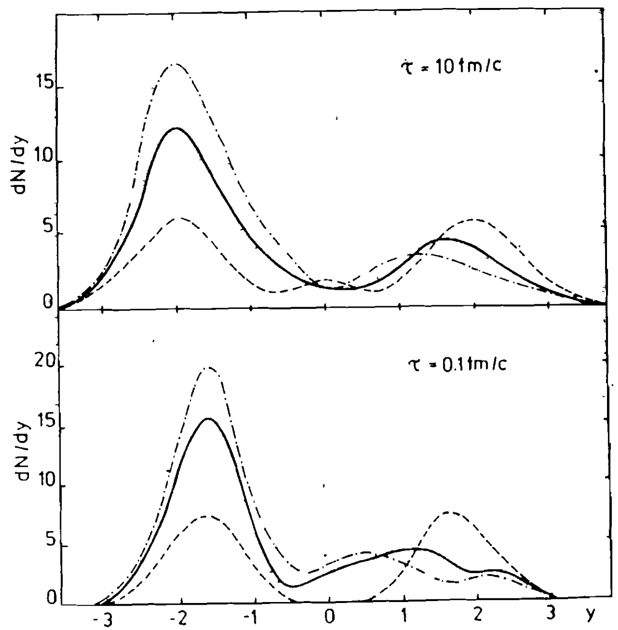

Fig. 4. Baryon multiplicity distributions for target slab thickness of 4.9 fm (dashed lines), 9.8 fm (solid lines) and 12.1 fm (dash-dotted lines) corresponding to target mass numbers of A=16, 120 and 240 for 200 GeV·A. The upper (lower) part is calculated for a hindered (rapid) phase transition.

peak stems from the target matter. A faster phase transition leads to a narrower distribution. This effect increases further with increasing drain term. Varying the target thickness we find that the position of the target peak remains unchanged whereas the projectile becomes very wide and splits finally. The increasing target size affects mainly the amount of projectile matter which sticks in the target region. As a net result the centre of gravity of the projectile distribution shifts to lower rapidity values.

The energy leak-out described by the drain term is considerable. The following values are obtained for Q = 2 fm^{-1}. For a symmetric collision at 200 GeV·A of two A=16 nuclei the energy leak--out amounts to 25% and at 60 GeV·A the percentage increases to 30%. For collisions of ^{16}O with a heavy nucleus 40% of the bombarding energy goes into the midrapidity region. Nevertheless the maximum energy density attained in the target fragmentation region is reduced only by 20%.

In slab geometry one cannot properly calculate the transverse energy and momentum distributions which arises mainly from the transverse expansion of the fluid. Instead we consider the maximum temperature averaged over the fluid which may serve as a guide for the characteristic dependences of the slope parameters. In fig. 5 we show this temperature as function of the target thickness. For a hindered phase transition this temperature increases with target size. This is due to the fact that the inertia of a heavier target allows a higher compression while the thin projectile already dissolves in the matter. Assuming a rapid phase transition most of the energy is consumed for the transformation and the temperature remains nearly constant. For 60 GeV A the temperature does not exceed the critical temperature of our model (T_{crit} = 167 MeV).

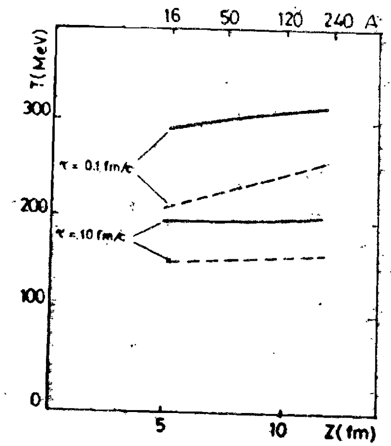

Fig. 5. Maximum temperatures averaged over target and projectile matter as function of target thickness for 60 GeV·A (dashed lines) and 200 GeV·A (solid lines).

5. Conclusions

In the present work we apply a two-fluid model, which allows for energy leak-out into the midrapidity region, to ultrarelativistic collisions of light projectile nuclei with various target nuclei. The predictions of the model foot on two yet poorly known parameters which determine the mutual stopping and the energy drain when the nuclei interpenetrate. We estimate these two parameters from the stopping power as dervied from p-A data analysis. Basing on these ingredients we present the baryon multiplicity distributions. The wideness of the distribution for the projectile seem to point to the fact that it is difficult to use a single value, such as the main rapidity loss, as a reasonable measure for the stopping power. Therefore, the comparison with detailed experimental data for several bombarding energies and targets should be used to extract more reliable the values of D and Q.

Our presently used values of D and Q point to the possibility of deconfinement in the fragmentation region at 200 GeV A; at 60 GeV·A only partial deconfinement can be reached. If, however, the deconfinement time scale is larger than 1 fm/c the matter disassembles before deconfinement can occur. We find that the maximum temperature which may serve as a measure of the slope parameters in the transverse spectra, are sensitive to the fact whether deconfinement happened or not.

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Барц Х.В., Кэмпфер Б. E2-87-794
Применение двухжидкостной модели
с энергетическим "оттоком" к асимметричным
столкновениям тяжелых ионов
при ультра-релятивистских энергиях

Ядерная прозрачность описывается в модели двух взаимопроникающих жидкостей. Учтено образование частиц в промежуточной области быстрот за счет оттока энергии из области фрагментации. Обсуждаются пространственно-временная картина столкновения, а также эффекты размера мишени и масштаба времени деконфайнмента.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

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Barz H.W., Kämpfer B. E2-87-794
Two-Fluid Model with Energy Leak-Out Applied
to Asymmetric Ultra-Relativistic Heavy-Ion
Collision

Nuclear transparency is described within a model of two interpenetrating fluids. The formation of the midrapidity region is included by the energy leak-out from the fragmentation regions. The space-time picture of the collision, the baryon multiplicity distribution and maximum temperatures as well as the effects of target size and deconfinement time scale are discussed.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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