KFKI-1984-53

L.P. CSERNAI
H.W. BARZ
B. KÄMPFER
B. LUKÁCS

EXTRA ENTROPY PRODUCTION DUE TO NON-EQUILIBRIUM PHASE TRANSITIONS IN RELATIVISTIC HEAVY ION REACTIONS

Hungarian Academy of Sciences

CENTRAL RESEARCH INSTITUTE FOR PHYSICS

BUDAPEST

KFKI-1984-53

EXTRA ENTROPY PRODUCTION DUE TO NON-EQUILIBRIUM PHASE TRANSITIONS IN RELATIVISTIC HEAVY ION REACTIONS

L.P. CSERNAI*

School of Physics and Astronomy
University of Minnesota, 116 Church Street S.E.
Minneapolis, MN-55455, USA

H.W. BARZ, B. KÄMPFER

Central Institute for Nuclear Research, Rossendorf,
DDR-8051 Dresden, Pf.19, German Democratic Republic

B. LUKÁCS

Central Research Institute for Physics
H-1525 Budapest 114, P.O.B.49, Hungary

HU ISSN 0368 5330
ISBN 963 372 231 4

* permanent address: Central Research Institute for Physics, H-1525 Budapest 114, P.O.B.49, Hungary

ABSTRACT

In a fluid-dynamical model the extra entropy production is calculated which arises from a non-equilibrium phase transition from nuclear to quark-gluon matter.

АННОТАЦИЯ

С помощью гидродинамической модели определяется избыток этнропии, происходящей от неравновесного фазого перехода нуклонов в кварки.

KIVONAT

Hidrodinamikai modellben meghatározzuk a nemegyensulyi nukleon-kvark fázisátmenetben produkált entrópiatöbbletet.

While energetic heavy ion collisions can produce dense and hot states of matter, out of reach in other experiments or even in astrophysics, the final detectation measures a diluted state, probably below normal nuclear density [1]. So, it is important to find such data which are directly connected with the hot, compressed state. Entropy seems to be the best candidate for this purpose, since its time variation is monotonous, and there are good arguments that it is produced mostly during the compression. Thus the specific entropy of the break-up stage is approximately the same as that at the maximal compression. Therefore entropy production is one of the most challenging problems in the heavy ion physics. If there is an excess in the observed entropy, that can be a signal for phase transition in the dense state [2].

While equilibrium phase transitions conserve the original entropy [3], non-equilibrium processes lead to an entropy excess [4]. Obviously, this excess depends on the ratio τ_{eq}/τ_{hyd}, where τ_{eq} is the characteristic time of the equilibration processes, while τ_{hyd} stands for some characteristic time for the hydrodynamic evolution. If this ratio is small, then there is an almost complete equilibrium, and the entropy production is small too. On the other hand, if this ratio is great, then the matter remains practically in the original phase during the whole collision, and the entropy production is small again. Thus one can expect the maximal entropy excess when tht two characteristic times are comparable.

Obviously, τ_{eq} should be determined from the microscopic description of the creation and growth of the new phase, however, this task is far from being trivial for such transitions as e.g. the nucleon-quark one, so a reliable result is still desired only. Nevertheless, the dependence of the entropy excess on τ_{eq} can be determined, and we study entropy production in this paper for the nucleon-quark phase transition. This problem was suggested in Ref. [4]. Here we present a realistic dynamical situation, where the one-dimensional flow motion of the matter is taken into account.

We consider two colliding slabs of nuclear matter with thickness approximately equal to the diameter of uranium. The matter is a viscous fluid, and we assume that

$$T_1 = T_2, \quad p_1 = p_2, \quad \mu_1 \neq \mu_2 \tag{1}$$

so there is no chemical equilibrium between the phases (T, p, and μ are the temperature, pressure and chemical potential, 1 and 2 denote the nuclear matter and quark phases, respectively). Further, we assume the transformation between the two phases obeys the general law [5].

$$\begin{aligned} \dot{\alpha} &= \Psi(T,n,\alpha) \\ \dot{\alpha} &\equiv \alpha_{,r}u^r \end{aligned} \tag{2}$$

where α stands for the ratio of baryons in phase 1 to the total number of baryons in a fluid element and n means the averaged density.

Then, using n_1, n_2 and T as characteristic quantities of the phases, the obvious balance equations are

$$T^{ir;}{}_{r} = 0, \tag{3}$$

$$(nu^r)_{;r} = 0, \tag{4}$$

$$p(T,n_1) = p(T,n_2), \tag{5}$$

where T^{ik} is the volume average of the energy-momentum tensors, and u^i the common velocity field. Since the quantities to be determined are u^i, n_1, n_2, n and T, an explicit form of eq.(2) is needed.

For this, we choose a linear approximation [5]

$$\dot{\alpha} = -q(\alpha - \alpha_{eq}), \tag{6}$$

where α_{eq} stands for the equilibrium value of α for given T and p. The parameter q has the dimension [1/time], so it is the inverse of τ_{eq} and should be in the order of the QCD scale $\hbar/B^{1/4} \sim 1c/fm$.

The equation of state in the nuclear phase is chosen the same as for a Boltzmann gas, plus a specific compression energy

$$E = (K/18)(n/n_o - 1)^2, \quad K = 280 \text{ MeV}, \tag{7}$$

while in the quark phase a free gas approximation is used [6], with the bag constant $B^{1/4} = 235$ MeV [7].

Firstly, let us consider an equilibrium phase transition ($q \to \infty$) in a fluid with the coefficients η and η' for the shear and bulk viscosities, respectively. Then, the entropy production per baryon is given by

$$\dot{s} = \frac{1}{Tn}\{\eta(u^{r;s} + u^{s;r} + u^t u^s u^r{}_{;t})u_{r;s} + \eta'(u^r{}_{;r})^2\} . \tag{8}$$

For a one-dimensional flow this expression reduces to

$$\dot{s}_1 = \frac{1}{Tn}\,\eta_{eff}(\dot{n}/n)^2 \tag{9}$$

with the coefficient $\eta_{eff} = 2\eta + \eta'$ of an effective viscosity. Secondly, ignoring the viscosity, one finds [4] for finite transformation rates q

$$\dot{s}_2 = -\frac{1}{T}(\mu_1 - \mu_2)\dot{\alpha} . \tag{10}$$

Including both effects the entropy productions according to eqs. (9) and (10) are not additive. There are cross terms because both the viscosity and the off-equilibrium processes do have influences on the velocity field. Nevertheless, eq. (10) gives an entropy excess due to the finite characteristic time of the transition processes, and we will calculate this excess and compare it to the total entropy.

We have solved eqs. (3)-(6) taking into account an effective viscosity according to ref. [8]. In *Fig. 1* we represent the time evolution of the total entropy and the extra entropy s_2 in eq. (10) for a typical bombarding energy of $E_{lab}/A = 7$ GeV and two rate factors q = 1 c/fm and 10 c/fm, respectively. At this energy a stable shock front with a finite thickness appears. Most of the entropy is produced during the compression state ($t < 5$ fm/c) essentially at the time when the shock front passes the fluid. After this time the entropy can only be produced in the phase transition which lasts a longer time for small transition rates q. Only 7% of the entropy are produced during the expansion stage ($5 < t < 15$ fm/c). A similar value was found for expanding and rehadronizing quark blobs with vanishing baryonic charge [9].

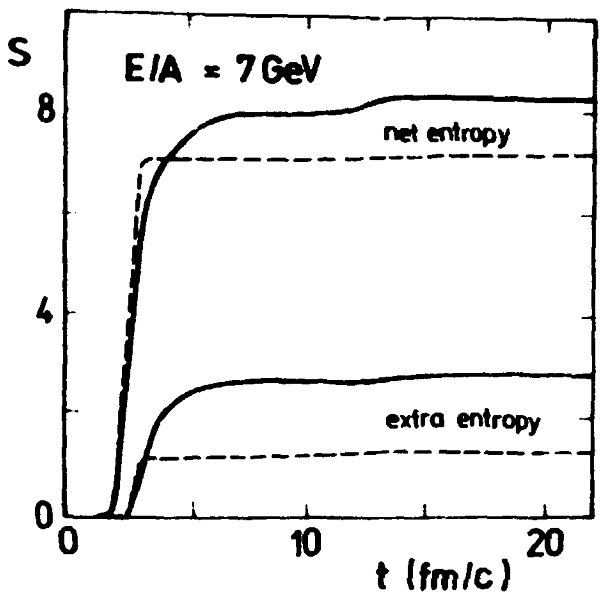

Fig. 1. *Entropy per baryon of the 8^{th} cell of two colliding uranium slabs (each consisting of 20 cells) as a function of c.m. time for two different conversion rate factors q at 7 GeV bombarding energy per nucleon (dashed curves: q = 10 c/fm, solid curves: q = 1 c/fm).*

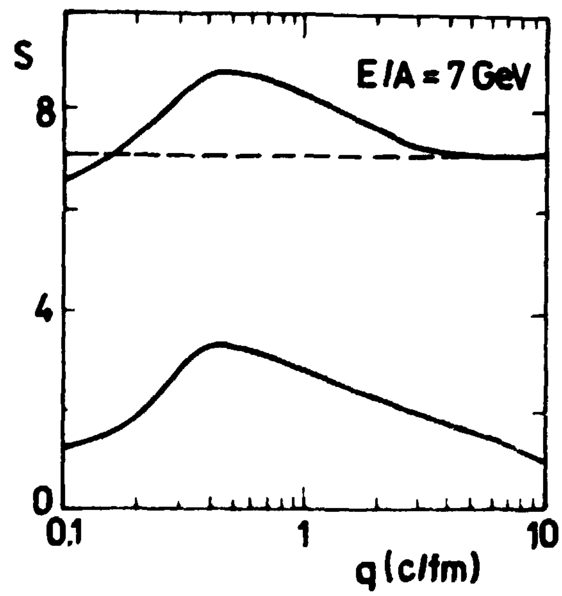

Fig. 2. *Entropy produced in the inner halves of colliding uranium slabs as a function of the rate factor q at 7 GeV bombarding energy per nucleon (upper curve: net entropy, lower curve: extra entropy). The dashed line indicates the entropy value for an instantaneous phase transition.*

Fig. 2 shows the behaviour of the entropy production as a function of the rate factor q for 7 GeV bombarding energy per nucleon. The maximum of the total entropy as well as of the extra entropy s_2 are found near q = 0.5 c/fm. We note further that the difference between the total and the extra entropy depends on the rate factor which shows that the phase transition influences the dynamics of the process. For large q the entropy approaches the value that is obtained from the shock model using the Rankine-Hugoniot-Taub-equations. For all energies between 5 and 10 GeV a maximal extra entropy of 1.5 units is produced.

In conclusion we have shown that for non-equilibrium phase transitions there is a considerable extra entropy production provided the transition is not too fast, i.e. $\tau_{eq} > \hbar/B^{1/4}$. In measuring the entropy at break up an entropy excess might signalize the phase transition to a transient quark-gluon plasma.

REFERENCES

[1] T.S. Biró, H.W. Barz, B. Lukács and J. Zimányi: Phys. Rev. C27, 2695 (1983)

[2] P.J. Siemens and J.I. Kapusta: Phys. Rev. Lett. 43, 1486 (1979)

[3] B. Lukács: Acta Phys. Pol. B14, 33 (1983)

[4] L.P. Csernai and B. Lukács: Phys. Lett. 132B, 295 (1983)

[5] G.E. Duvall and R.A. Graham, Rev. Mod. Phys. 49, 523 (1977)

[6] J.I. Kapusta: Nucl. Phys. B148, 461 (1979)

[7] P. Hasenfratz et al.: Phys. Lett. 95B, 299 (1980)

[8] G. Buchwald, L.P. Csernai, J.A. Maruhn, W. Greiner and H. Stöcher: Phys. Rev. C24, 135 (1981)

[9] B.L. Friman, G. Baym and J.P. Blaizot: Phys. Lett. 132B, 291 (1983)

Kiadja a Központi Fizikai Kutató Intézet
Felelős kiadó: Szegő Károly
Szakmai lektor: Révai János
Nyelvi lektor: Dolinszky Tamás
Gépelte: Berron Péterné
Példányszám: 450 Törzsszám: 84-274
Készült a KFKI sokszorosító üzemében
Felelős vezető: Nagy Károly
Budapest, 1984. április hó