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LARGE SCALE AND SMALL SCALE ENERGY TRANSPORT IN RELATIVISTIC NUCLEAR REACTIONS

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Abstract. The possibility of large scale and small scale energy transport between nucleons during relativistic collision process is examined and critically discussed in view of recent Monte-Carlo calculations. Deviations from a purely hydrodynamical motion are exhibited.

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Extensive measurements of proton inclusive cross sections in central nuclear collisions have revealed that the system (of participants) is thermalized to a large extent. This suggests that a long range communication has set up in the system. By this, we mean that any nucleon in the system has been connected through a chain of binary collisions to any other nucleon. Of course, these collisions must be "violent" (see below for a clarification of this concept) in order to speak of communication. This idea is embodied in the simplest way by the so-called fireball model (FM)[1].

The description of the collision by means of hydrodynamical equations (HE)[2,3], as strongly defended by the Frankfurt group, implies another type of communication. In this picture, local thermal equilibrium is assumed. The system can be viewed as divided into cells. Within cells, strong communication is established, while weak communication connects different cells. Actually, the HE govern how this weak communication is transmitted.

On the opposite, the knock-out model (KOM)[4] gives rather satisfactory agreement with the proton (and pion) spectra though, physically, it implies quite a different motion, characterized by a very small amount of communication : projectile nucleons are assumed to collide at most once with target nucleons.

These three pictures may be unified by considering that elementary two-body collisions establish strong communication within cells. In the HE, the cell dimension, say ~ 1 fm, is smaller than the characteristic linear dimension of the system of nuclear participants. In marked contrast, the KOM, roughly speaking, corresponds to a cell larger than the nuclear system. Finally, the FM takes the nuclear system itself as a single cell. It is generally stated that the dimension of the cell is given by the nucleon mean free path. The latter quantity is, however, unambiguously defined for an homogeneous and extended system only. In relativistic nuclear collisions, we are far from these ideal conditions and presumably the mean free path is not a relevant quantity. Nevertheless, we will try to get some information about the communication between nucleons during the collision process.

Present experimental data do not really permit to decide which picture is correct. We indicate below why inclusive measurements are not very useful in this respect. Two proton correlation measurements are still too scarce to privide a decisive test. However, there is some indication[7] that the physical reality corresponds neither to the FM nor to the KOM limits, but probably to a more complex situation.

We turn to three-dimensional cascade model to look for some clue. We especially consider recent Monte-Carlo calculations[5,6], where all the sequence of baryon-baryon collisions is followed. They yield the more reliable description of nuclear collisions in the collision regime and they potentially contain both the hydrodynamical and the rarefied gas regimes if the baryon-baryon collision cross section were modified in a suitable way. These calculations are described extensively in ref. 6. Suffices here to mention that pion production is introduced through the production of Δ-resonances and that these calculations are able to reproduce one-particle and two-particle measurements[5].

A first result is given in fig. 1, which exhibits calculated inclusive longi-

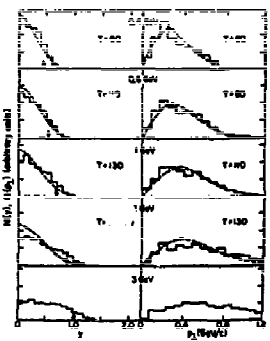

Fig. 1. Ca + Ca. Calculated proton rapidity and perpendicular momentum distribution for different incident energy (histograms). Fit by thermal distributions (dashed lines).

tudinal and transverse (relative to the beam axis) proton spectra. They are fairly well thermalized and support the FM. There is a systematic deviation, however : the longitudinal temperature is larger than the perpendicular temperature, a feature which may be related to the observed forward-sideward asymmetry[7].

Baryon density distribution has been calculated within this model and presents interesting aspects in view of a comparison with HE results. Fig. 2 shows the density profile in a central collision between Ne + Ni at 1 GeV/A . Clearly a strong discontinuity is propagating and may be tentatively interpreted as a shock wave. Study of temperature, of the entropy, of the current of entropy ahead and beyond the discontinuity is however needed before accepting such an interpretation.

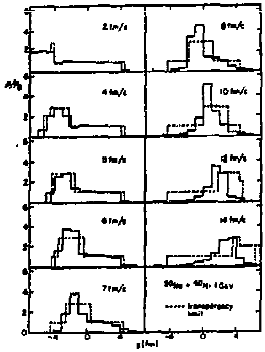

Fig. 2. Baryon number density profile along the beam axis for a central collision of an incident Ne nucleus on a Ni nucleus in the lab system, for different times. At t=0, the target is located at z=0 and the projectile coming from the left is just touching the target.

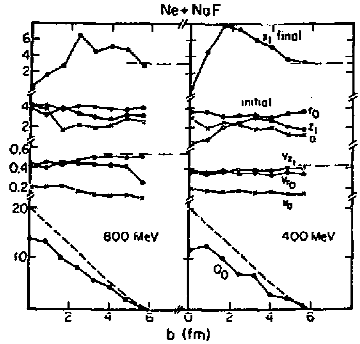

Fig. 3. Ne + Na F, E_{beam}/A = 800 and 400 MeV. Values of the parameters from eq. (1) below. The dashed curve gives the number of participants as predicted by the clean-cut geometry.

It has been shown[6,7] that Monte-Carlo calculations support the idea of a clean splitting of the system into a participant and two spectator parts. The density distribution of a symmetric system in the late stages of the collision process are remarkably fitted[8] by a sum of three expanding gaussians :

$$\rho(\vec{r},t) = \frac{Q_o}{\pi^{3/2}\, r_o^3}\, e^{-r^2/r_o^2} + \frac{Q_1\, \gamma_1}{\pi^{3/2}\, a^3} \{\exp(-[(x-x_1)^2 + y^2 + (z-z_1)^2\, \gamma_1^2]/a^2) +$$

$$\exp(-[(x+x_1)^2 + y^2 + (z+z_1)^2\, \gamma_1^2]/a^2)\} \quad . \qquad (1)$$

The parameters Q_o and Q_1 are fairly constant, while r_o , a , x_1 and z_1 are almost linear functions of time :

$$\{r_o,a,x_1,z_1\} = \{r_o(t_o),a(t_o),x_1(t_o),z_1(t_o)\} + (t-t_o)\, \{v_{r_o},v_a,v_{x_1},v_{z_1}\} \quad . \qquad (2)$$

The parameter γ_1 is the Lorentz factor relative to v_{z_1} . The values of the parameters are given in fig. 3 for the Ne + Na F system. Two remarks are in order :

(a) As in the HE approach, the spectator parts do not travel along straight lines (see values of x_1) : they are deviated sideways. However, the amplitude of this kick-off effect is quite smaller than what is claimed in ref. 3.

(b) The participant part is smaller than what is predicted by the clean-cut geometry argument, especially for central collisions. Obviously, this is not an hydrodynamical feature. In ref. 2, this transparency effect has been simulated by assuming the two nuclei made of different fluids interacting weakly. The prediction of this effect may be checked by looking at possible clusters emitted with the incident rapidity in the forward direction during high multiplicity events.

In ref. 9, the communication between nucleons is studied in the frame of Monte-Carlo calculations in the following way. For every event, the system is divided into clusters (of M projectile particles and N target particles) that are dynamically correlated. By this, it is meant that any nucleon of this cluster is connected to any other one of the same cluster by two baryon collisions involving nucleons of this cluster only. The "intensity" of the connection (or the communication) is characterised by the absolute value of the four momentum transfer of the collisions $q = \sqrt{-t}$ (the s channel is always chosen as the baryon-baryon channel). The soft collisions (or weak communication) can be disregarded by considering collisions with $q \geq q_{min}$ only. In principle, the analysis of the probability $\sigma(M,N)$ of having a cluster (M,N) would allow to discriminate between the three pictures outlined at the beginning. If the hydrodynamical picture was correct, the distribution of $\sigma(M,N)$ would be concentrated around $M = \bar{A}_{p_1}$, $N = \bar{A}_{p_2}$, for $q_{min} = 0$, where $\bar{A}_{p_1}$ and $\bar{A}_{p_2}$ are the average number of participant nucleons coming from each nucleus in the clean-cut geometry picture. When q_{min} is increased, the peak of the distribution would move, rather abruptly for some value of q_{min}, to small values of (M,N), say $2 \sim 4$. This value q_H must be related to the weak communication typical of hydrodynamics, which is examplified by sound waves. Using typical value for the sound velocity v_s, we find $q_H = \frac{1}{2} m_N v_s^2 \sim 200$ MeV/c. If the FM was correct, the $\sigma(M,N)$-distribution would peak around $(\bar{A}_{p_1},\bar{A}_{p_2})$ independently of q_{min} less than q_T, which may be estimated as the typical transfer in a thermalized system. Using the empirical value of the temperature τ (~ 80 MeV), we get $q_T = \sqrt{2\, m_N\, \tau} \sim 400$ MeV/c. If the KOM was correct, the $\sigma(M,N)$-distribution would peak for small values of (M,N), say $M = N = 1$ to 2, independently of $q_{min} < q_K$ which may be taken as the average transfer in the nucleon-nucleon collision at the appropriate energy. At 800 MeV/A, $q_K \sim 400$ MeV/c.

Fig. 4 shows the mean cluster size $\langle M+N \rangle$ as a function of q_{min}. The varia-

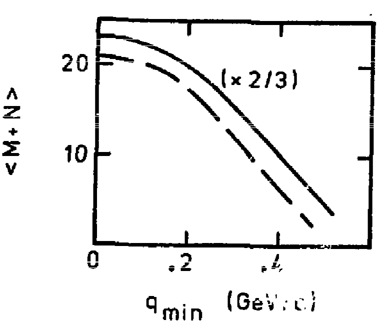

Fig. 4. Mean cluster size $\langle M+N \rangle$ as a function of q_{min} for the Ca + Ca system (full line, for central collisions only) and for Ne + Ne system (dashed line, for all impact parameters) at $E_{beam}/A = 800$ MeV.

tion does not fit in any of the behaviours explained above. Fig. 5 gives the $\sigma(M,N)$-distribution for q_{min} = 250 MeV/c . All these results indicate a situation

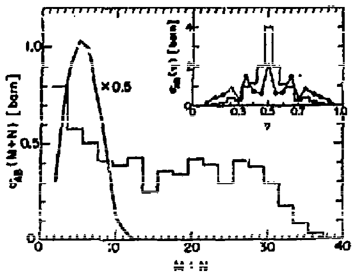

Fig. 5. *Probability $\sigma(M,N)$ for the formation of a cluster of size (M,N) as a function of $M+N$, for all values of $\eta = M/(M+N)$ and as a function of η for all values of $M+N$. The histograms are given by Monte-Carlo calculations. The curves are the result of a one-dimensional cascade calculation.*

more complex than predicted by any of the three models, and probably a coexistence of the typical features of these models.

It is explained in ref. 9 why any of the three models gi es very similar results for the inclusive cross sections. The latter are given by

$$E \frac{d^3\sigma}{dp^3} = \sum_{MN} \sigma(M,N)\ F_{MN}(\vec{p}) \quad , \tag{3}$$

where $F_{MN}(\vec{p})$ is the momentum distribution within the cluster (M,N) . All the functions F_{MN} have practically the same $\vec{p}$ dependence, close to the ones given by the statistical limit, except for $M = N = 1$. Grossly speaking, any $\sigma(M,N)$-distribution with a reasonable value of $\sigma(1,1)$ can give the main properties of the inclusive cross sections (see ref. 9 for more detail).

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