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CAN RECENT CERN EXPERIMENTS WITH 200 GeV/N O^{16} IONS BE EXPLAINED BY THE INDEPENDENT NN COLLISIONS?

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НОВОСИБИРСК

Can Recent CERN Experiments with 200 GeV/N O^{16} Ions be Explained by the Independent NN Collisions?

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ABSTRACT

The physical picture suggested by a number of «independent NN collisions» models is criticized. We argue that neither the strings may break independently, nor secondaries may escape from the system without multiple rescattering. Similarity of the $p_{\perp}$ spectra in O Pb and pp collisions is just a manifestation of their thermal nature. Some predictions are made for the heavy ion collisions.

This paper is a reaction to the widespread opinion (see e. g. talks at «Quark matter-87» [1] or the report of the experiment leaders [2]) that the data mentioned have shown that such collisions are «more or less a superposition of the NN ones» . We argue that it cannot be so, both for the production of secondaries and their «final state interaction». The transverse energy and multiplicity distributions, as well as the $p_{\perp}$ spectra of secondaries were indeed reproduced by the «independent NN collision» models [3, 4], but such agreement is misleading: these quantities are insensitive to the final state interaction. Those which are sensitive (e. g. interferometric measurements) strongly disagree with these models.

The physical picture behind the models [3, 4] is as follows: while passing through each other, the «partons» exchange color, and then a set of strings is formed. Three assumptions made are as follows: (i) strings are formed independently; (ii) their decay into secondaries are independent too; (iii) final state interaction of the secondaries can be neglected. (Parameters of the strings, their formaton and breaking are taken from some multiparameter fit to the *pp* and *pA* data.) But can these assumptions really be justified? Assumption (i) may well be reasonable: color is transfered by the short-range gluon exchanges. However, as partons go ahead, the strings also expand transversely, trying to reach their normal transverse size R_{string}. They are independent if the string density n_{string} (per transverse area) is small enough

$$\pi R^2_{string}\, n_{string} < 1 \qquad (1)$$

n_{string} can be estimated from the models themselves: for the largest multiplicity O-Pb collisions $n_{string}=3\div 10\ \text{fm}^{-2}$.

The value of R_{string} is rather uncertain, if it is about 1 fm then (1) is certainly violated. Even if R_{string} is much smaller in vacuum, it is difficult to imagine it to be small in such dense matter. (Lattice calculations suggest at such density either complete deconfinement, or strings with smaller tension and larger R_{string}.) But even for infinitely thin strings, the picture of the noninteracting «rope» of them is too naive: it is a classical picture, while strings have quantum fluctuations. According to the rules of the string model, strings exchange their parts if crossed. For example, two opposite-flux strings can collapse into a closed ones (see Fig. 1,*a*), while strings of the same flux may glue into the double-flux one (see Fig. 1,*b*), with stronger field and much shorter lifetime. First estimates [5] have suggested the lifetime for such a «color rope» of only about 1/3 fm/c1), much shorter than for a single string. Thus, assumption (ii) is very questionable.

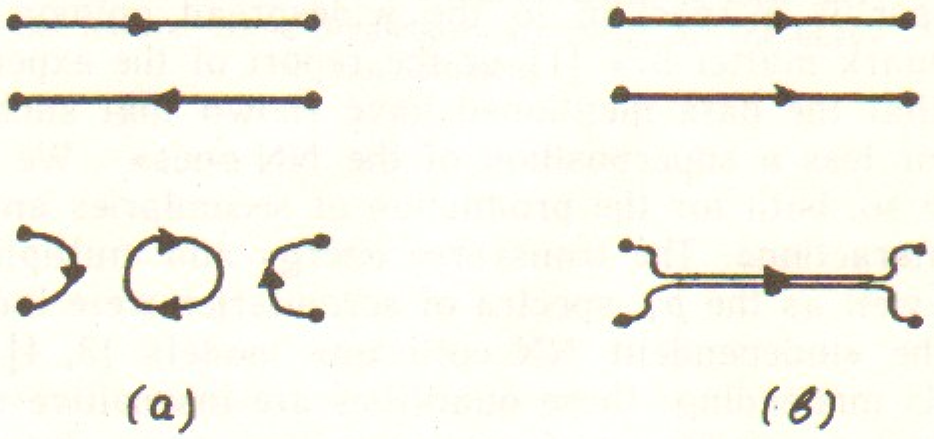

Fig.1. Schematic picture of string interaction: the opposite flux tubes are collapsed (*a*) while the same flux ones are glued together (*b*).

Now we turn to the assumption (iii). Whatever is the mechanism of the quark pair production and «hadronization» , the role of the final state interaction of secondaries can well be estimated. We know the cross sections (at low relative energies they are dominated by few resonances) and may calculate the mean free paths. As the simplest example we take a gas of pions, and, following [6], use the detailed balance method. In equilibrium the rate for (any number of) pions to form a resonance (e. g. the ρ-meson) is equal to its inverse decay rate, and the latter is simpler to estimate:

$$\frac{d^4W}{dx^4}=\sum_i \tilde{\Gamma}_i n_i(T);\qquad n_i(T)=(2I+1)(2S+1)\left(\frac{m_iT}{2\pi}\right)^{3/2}\exp\left(-\frac{m_i}{T}\right). \tag{2}$$

Here $n_i(T)$ is just the equilibrium density of a resonance and $\tilde{\Gamma}_i$ is its width in a gas (which differs with its value Γ_i in vacuum due to the «final state» factors $(1\pm f)$. $f=(\exp(E/T)\mp 1)^{-1}$ is the occupation numbers for Bose (Fermi) secondaries). $\tilde{\Gamma}_i$ are somewhat larger2) than Γ_i: for example, at $T=200$ MeV their values are about 30, 210, 200 MeV for ω, ρ, *f* mesons, while in the vacuum they are 10, 150 and 180 MeV, respectively. Convolution of (2) with the «temperature profile» function $\Phi(T)$ [6] gives the total number of the decays per collision:

$$N_{decays}=\int\frac{d^4W}{dx^4}d^4x=\int dT\,\Phi(T)\frac{d^4W}{dx^4} \tag{3}$$

Making an estimate, one may just divide the rates by the pion density and find the rate per pion of the resonance formation. For two typical temperatures, the «hadronization» and the «breakup» ones they are as follows

$$\tilde{\Gamma}_\pi=\begin{cases}200\ \text{MeV} & (T=T_c\simeq 200\ \text{MeV})\\ 45\ \text{MeV} & (T=T_f\simeq 140\ \text{MeV})\end{cases} \tag{4}$$

Scattering rates fall rapidly at smaller *T*, and the breakup occures for T_f such that

$$\tilde{\Gamma}_\pi(T_f)\,\tau_{lifetime}\sim 1 \tag{5}$$

Now, what is the lifetime of the system $\tau_{lifetime}$? The interferometric data of the NA35 collaboration (see [1, 2]) show that in the central rapidity there is a «fierball» with the transverse and longitudinal radii equal to

$$R_\perp=8.3\pm 1.2\ \text{fm};\ R_\parallel=7.0\pm 1.8\ \text{fm}\,. \tag{6}$$

(By the way, according to any independent collision model $R_\perp$

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1) Quite similar result was obtained about a decade ago in [6], where the mean free path of a gluon in a quark-gluon plasma of comparable energy density was estimated. Similar numbers for «mixing time» follow from the «parton cascades» models as well.

2) It would be interesting to measure these deviations experimentally.

should be just the radius of the oxigen nuclei, $\simeq 3$ fm.) Transverse expansion should be slow (see below), so, considering (6), the lifetime should be[3] about 10 fm/c or more. Thus, secondaries definitely have enough time to be rescattered *several times*.

The data show that the $p_\perp$ spectra of secondaries in O-Pb collisions are roughly the same as in the *pp* ones. This fact seems natural for the independent scattering models. If multiple rescattering is there, why the spectra are not affected by them? However, similarity of these spectra is also natural in the multiple rescattering regime because (as discovered by Boltsmann) rescattering do not affect the spectra corresponding to the thermal equilibrium. Thus, we reverse the argument and consider similarity of *pp* and O-Pb data as evidence for local thermal equilibrium (at least at the latest stage of the process) already in the *pp* collisions!

One may also ask why one observes only thermal spectra, without collective (hydrodynamical) effects? The answer suggested in [7] (and later supported by lattice data) is as follows: the equation of state is in fact very «soft», (with small pressure ($p/\varepsilon \ll 1$) in this region due to the phase transition, separating hadronic matter from the quark-gluon plasma. Thus, the absence of prominent hydrodynamical effect is a signal for the phase transition!

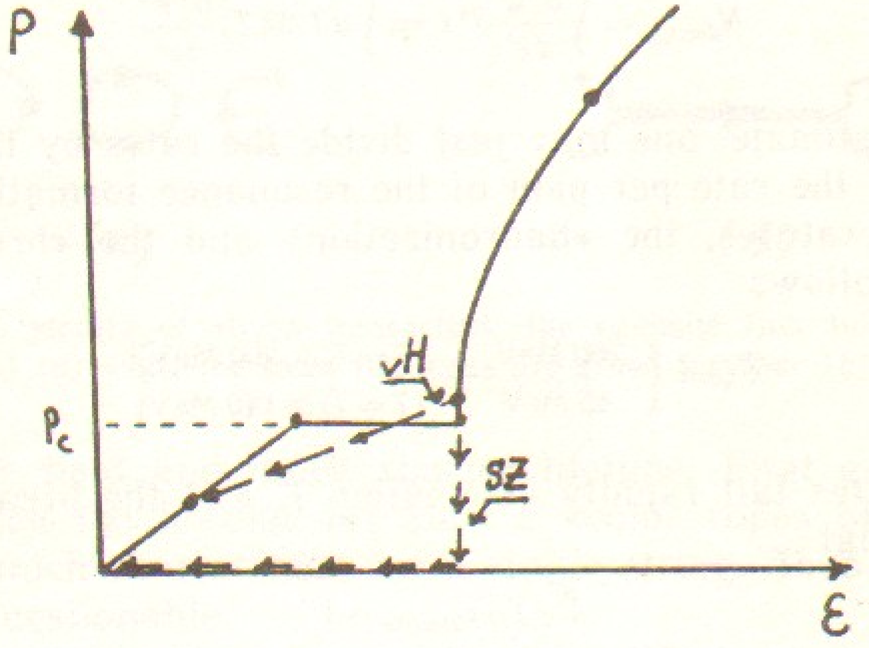

Fig.2. Sketch of the equation of state as pressure p versus the energy density ε. Arrows show two limiting scenarios of matter cooling, see text.

A sketch of «modern» equation of state is shown in Fig. 2. Two limiting scenarios for matter cooling are as follows: the arrow line «SZ» [7] corresponds to slow «hadronization», leading to «mechanically stable» ($p=0$) overcooled plasma droplets[4]. Another scenario due to L. van Hove [8] is based on instantaneous hadronization at the deflagration front. Although deflagration may lead to significant collective flow rapidity $y\sim 1$ [8], only small fraction of the matter may obtain it: velocity of the front itself is very small.

Let us briefly consider the spectrum shape, discussing what happens for heavy ion collisions. The maximal observed multiplicity for O-Pb is $n_{ch}\simeq 500$, while for heavy ion collisions at the same energy/baryon one expects it to reach about 10^4. The system lifetime becomes several times larger, as well as the number of rescattering. And nevertheless we predict that the main changes in the *p* spectra are only slight decrease of the break-up temperature $T_{\text{break-up}}$ according to (5).

The $p_\perp$ spectra are known to deviate from $\exp(-m_\perp/T)$, $m_\perp^2=p_\perp^2+m^2$, in the $p_\perp=1-4$ GeV/c region. There are two mechanisms which were used to explain it: (i) evaporation at earlier stages; (ii) the deflagration mentioned above. (Note that for large systems both are a kind of surface phenomena.) Specific feature of the deflagration is the well fixed value of the flow rapidity: then heavy secondaries (K, p...) should obtain more or less fixed value of their p, developing a «shoulder» in the spectra. Evaporation is connected with the interplay of the Boltsmann factor $\exp(-m_\perp/T)$ and the temperature profile $\Phi(T)$. For the equation of state shown in Fig. 2 the system spends much time in the mixed phase, and $\Phi(T)$ has a contribution like $\delta(T-T_c)$. If so, the observed spectra has strong contribution of the type $\exp(-m_\perp/T_c)$. It may be

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[3] The «source lifetime» measured still has too large errors, it is in the range 0. —4.5 fm/c. Note, however, that it is smaller than the actual lifetime of the system: while particles are «trapped» by the interaction the «source» is not seen. (If the break-up condition is fulfilled simulteneously in the whole fierball, the «source» may flash instantly.)

[4] L. van Hove (private communication) have suggested an argument, that (at least in some rare events) the long-lived large objects with the balanced pressure are seen. They are the so called ring-type events, in which many (say, 10) pions are grouped in some small rapidity interval (say, 0. 5 or even 0. 1). (One of the first one was observed by the UA5 group at CERN, now they are seen in other data, well above any statistical background.) The spread of longitudinal momenta is very small: from uncertainty principle it folllows that particles are emittied from some long and very cold object. It may well be a plasma droplet, pressure balanced in transverse direction and «overcooled» by the longitudinal expansion.

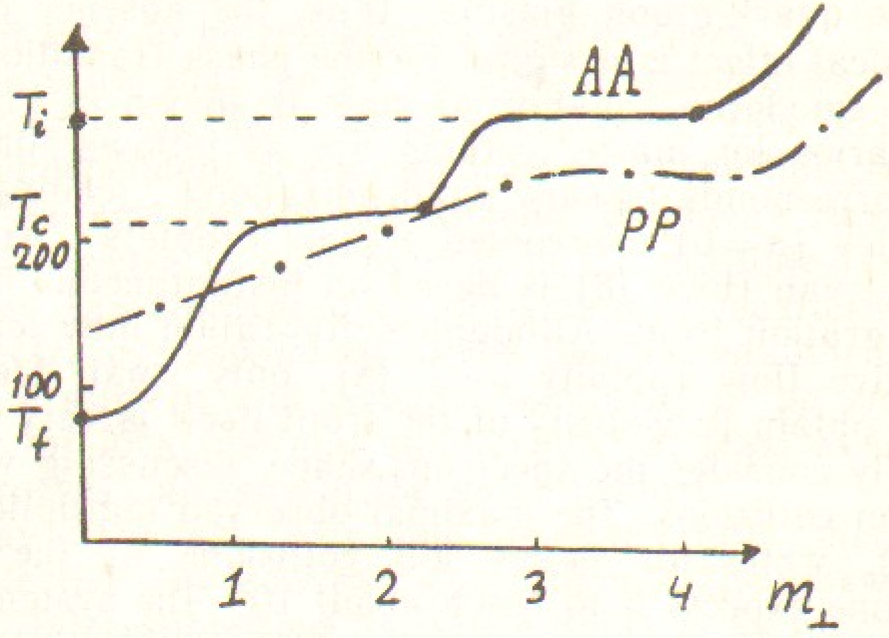

Fig.3. Schematic picture of the predicted dependence of the effective slope T_{eff} (7) on $m_\perp=\sqrt{m^2+p_\perp^2}$ for heavy ion collisions (solid curve). The dash-dotted line shows the *pp* data for comparison.

revealed either by the inverse Laplas transform, or simply by plotting of the «local slope» versus $m_\perp$ (Fig. 3)

$$T_{eff}(m_\perp)=\left(\frac{d}{dm_\perp}\log\frac{d\sigma}{dp_\perp^2}\right)^{-1} \tag{7}$$

and looking for some «plateau» at $T=T_c$ (and, may be, at initial temperature T_i). Some indications for such plateau were already found in the ISR data [9].

In conclusion, we have shown that «collisionless» picture suggested by a number of models contradicts to simple estimates and to some observations. However, the multiple rescattering regime also explains similarity of *pp* and O-Pb spectra, provided they are close to the thermal ones. As the collective (hydrodynamic) effects are not seen, one may conclude that the equation of state is indeed «soft» enough, signalizing the phase transition. Different interpretation of the medeate ($p_\perp=1\div4$ GeV) region of spectra are possible. Whatever the mechanism of their generation turns to be, the experimental data considered are very far from being «trivial», and further work with much larger systems is obviously justified.

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(See also in: *E.V. Shuryak*, Lectures, CERN 83-01.)

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Можно ли объяснить результаты экспериментов по соударениям ядер кислорода с энергией 200 ГэВ/нуклон в моделях независимых соударений?

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