PREDICTIONS FOR TRANSVERSE ENERGY DISTRIBUTIONS IN HEAVY ION COLLISIONS FOLLOWING FROM A SIMPLE NO-PLASMA MODEL*

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A simple model is described which reproduces qualitative features of the recent data on large transverse energy (E_T) distributions in proton-Pb collisions at 200 GeV/*c* obtained by the HELIOS collaboration at CERN. The same model is used to predict the E_T distributions in ^{16}O-^{238}U collisions. The model is based on the assumption that each of the wounded constituents (nucleons or quarks) in the nucleus gives rise to a "string" in the target fragmentation region. Both the number of "strings" and the number of soft hadron pairs produced from a single string within a given rapidity interval are assumed to be Poisson distributed stochastic quantities. The total E_T is assumed to be built up by contributions of soft hadrons. We argue that the signature of plasma formation could be seen as an excess of events above the model predictions in the large E_T tail of the E_T-distributions.

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1. Introduction

The first results are expected to come soon from experiments dedicated to the search of quark-gluon plasma in heavy ion collisions. The existence of plasma follows from the QCD (for reviews see [1–5]) although it is not precisely known what energy densities are required and whether they can be reached in heavy ion collisions. The estimates based on the experimental data on nucleon-nucleon and nucleon-nucleus collisions and on expected transition parameters indicate that the plasma might be formed in heavy ion collisions both in the fragmentation [6] and in the central [7] regions.

On intuitive grounds it seems probable that events with large total transverse energy and without jets due to hard scattering could be a good place for looking for plasma forma-

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tion. The large total transverse energy could be caused by the transverse flow of the expanding plasma. The data on large transverse energy events in ^{16}O-^{238}U collisions will be obtained, probably already this fall, by the HELIOS collaboration at the CERN SPS. As a first stage of the experiment the collaboration has recently studied [8] large E_T events in proton--Pb collisions at 200 GeV/c incident proton momentum. The E_T in this experiment has been the sum of transverse energies of all particles produced within the lab. pseudorapidity interval $0.6 < \eta < 2.4$. The data contain, although with a probability of about 10^{-6}, also events with $E_T > 50$ GeV, what is by a factor of 2.5 larger than the kinematic limit $\sqrt{2E_{Lab}m_p} = 20$ GeV for a proton-proton interaction. In a collision of proton with a cluster consisting of n nucleons the kinematic limit is $\sqrt{2E_{Lab}nm_p}$ and the data seem to require collisions with cluster of $n \sim 9$. This line of thinking is however misleading. Another possibility how to get over the kinematic limit is indicated by the parton model. Suppose that the incident proton consists of n partons, each of them with energy E_{Lab}/n. The kinematic limit for the transverse energy released in n collisions of constituents with nucleons within the nucleus is then $n\sqrt{2(E_{Lab}/n)m_p}$. An event with $n \sim 9$ can well lead to large E_T events observed by the HELIOS collaboration. This argument indicates that the large E_T events might be explained also by models in which secondary particles in the p-Pb collisions are originated by many independent sources, each of them with a limited E_T.

In the recent note [9] we have proposed a simple model of large E_T events in p-Pb collisions which describes in a qualitative way the data [8]. The role of independent sources is played by "strings" attached to the "wounded" nucleons in the Pb-nucleus.

We shall first describe this simple model and the results obtained [9] for p-Pb collisions (Sect. 2). Then, in Sect. 3, we shall extend the model to ion-ion collisions. The predictions of the model depend on whether the strings are attached to wounded nucleons or to wounded quarks and we shall therefore consider both options. Section 4 contains some details of the model. In Sect. 5 we present comments and conclusions, in particular we discuss here a possible QCD plasma signature in E_T distribution. Some formulae on the compound Poisson distribution are summarised in the Appendix.

2. *Simple model of E_T-distributions in proton-nucleus collisions*

The simple model [9] does not pretend to be a theory of a complicated process of proton-nucleus collision, its aim is to describe the qualitative features of large E_T-distributions.

In this model the large total E_T is built up as a sum of a large amount of contributions due to soft final state hadrons, each of them having a transverse energy of about 0.4 GeV. In more detail the assumptions of the model are:

(*i*) In a hadron-nucleus collision each of the "wounded" constituents in the nucleus gives rise to a "string" which then decays into the final state hadrons. This number of strings concerns the nucleus fragmentation region, at higher rapidities the strings join. The idea of independently fragmenting strings has been built into numerous models of hadron-nucleus and nucleus-nucleus collisions [10–13]. As an example we show in Fig. 1

the picture of the hadron-nucleus collision in the model of Białas, Czyż and Leśniak [10]. At each of the wounded quarks starts a string which later on joins with other strings. It is not clear-at least to us what is the average rapidity length to the joining point, neither is it clear whether the strings originated within the same nucleon do not join earlier than strings from different nucleons. To be conservative, we shall assume that the strings originated within the same nucleon join rather early and that effective number of strings in the whole

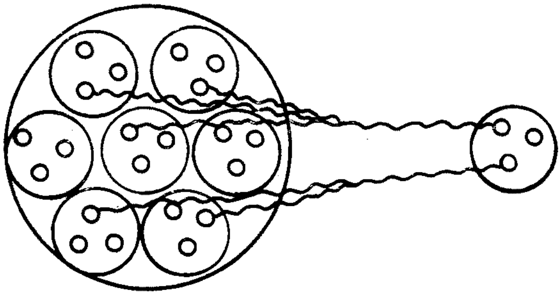

Fig. 1. The formation of strings in a hadron-nucleus collision according to the model of Białas, Czyż and Leśniak [10]

target fragmentation regions is roughly equal or only slightly higher than the number λ_p of wounded nucleons[1]

$$\lambda_p \equiv \langle \nu \rangle = \frac{A\sigma_{pn}}{\sigma_{pA}}, \tag{1}$$

where σ_{pn} is the non-diffractive proton-nucleon and σ_{pA} the proton-nucleus cross-section. Taking $\sigma_{pn} \sim 30$ mb and $\sigma_{pA} = \sigma_{pPb}\,(\mathrm{exp}) = 1747$ mb we obtain $\lambda_p \sim 3.8$. As mentioned above λ_p should be in fact somewhat larger. Phenomenologically λ_p could be determined as the ratio

$$\lambda_p = \frac{\langle dn/dy \rangle_{pA}}{\langle dn/dy \rangle_{pp}}$$

in the target fragmentation region.

(*ii*) The distribution in the number N of strings is Poissonian, with the expectation value λ_p.

(*iii*) Each of the final state hadrons produced by a fragmentation of a string has the average transverse energy $\varepsilon_T \sim 0.4$ GeV. This follows from the data [14, 15] which indicate that within the energy regions of the SPS and CERN-ISR the transverse energy distribution of soft final state hadrons is practically independent of the energy of the incoming hadron. To simplify the discussion we shall first assume that each of the final state hadrons has exactly $\varepsilon_T = 0.4$ GeV. Later on in Sect. 4 we shall consider more realistic ε_T-distribution. It will turn out, however, that this difference has no effect on the total transverse energy distributions.

[1] If quark strings join only after the fragmention region, the number of strings becomes $\lambda_Q = 3A\sigma(qn)/\sigma(pA) = [A\sigma(pp)/\sigma(pA)]\,[3\sigma(qn)/\sigma(pp)] = [A\sigma(pp)/\sigma(pA)] * 1.3 = 1.3\,\lambda_p$.

(*iv*) The average rapidity density of hadrons produced by a fragmentation of a particular string is the same as in the e^+e^- or hadron-hadron collision — about 3 hadrons per rapidity unit. Within the pseudorapidity interval $0.6 < \eta < 2.4$ covered in the HELIOS collaboration experiment [8] we thus expect in average 5.4 final state hadrons.

(*v*) The distribution in the number of hadron *pairs* in a given rapidity interval is Poissonian. This is motivated by the fact that particle multiplicities in lower energy hadron-hadron or e^+e^- collisions are well described by the Poisson distributions in the number of *pairs* of hadrons. The average number of hadron pairs from a particular string within the rapidity bin $0.6 < \eta < 2.4$ is thus $\mu \sim 2.7$.

The distribution $P(n)$ of hadron pairs within the pseudorapidity interval $0.6 < \eta < 2.4$ is then given by the compound Poisson distribution

$$P(n) = \sum_{N,n_1,n_2,\ldots n_N} P_S(N)P_h(n_1) \ldots P_h(n_N)\delta(n - \sum_{1}^{N} n_i), \tag{2}$$

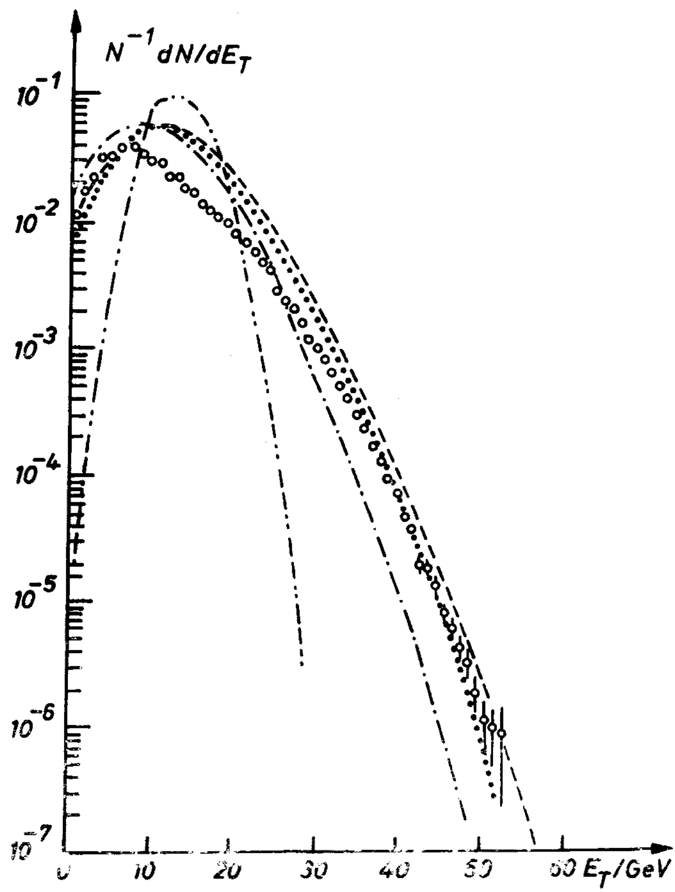

Fig. 2. The comparison of data on E_T-distribution in p-Pb collisions at 200 GeV/c with compound Poisson distributions, data — circles, compound Poisson with $\mu = 2.7$ and $\lambda_p = 4.5$ — dash-dot, with $\mu = 2.7$ and $\lambda_p = 5.5$ — dot, with $\mu = 3$ and $\lambda_p = 5$ — dash. Simple Poisson with $\langle n \rangle = 15$ — double dash, double dot

where

$$P_S(N) = \frac{\lambda_p^N}{N!} e^{-\lambda_p} \tag{3}$$

is the Poisson distribution of the effective number of strings in the fragmentation region, and

$$P_h(n_i) = \frac{\mu^{n_i}}{n_i!} e^{-\mu} \tag{4}$$

is the Poisson distribution of the number of hadron pairs originated from the i-th string. Each hadron pair contributes 0.8 GeV to the total transverse energy E_T.

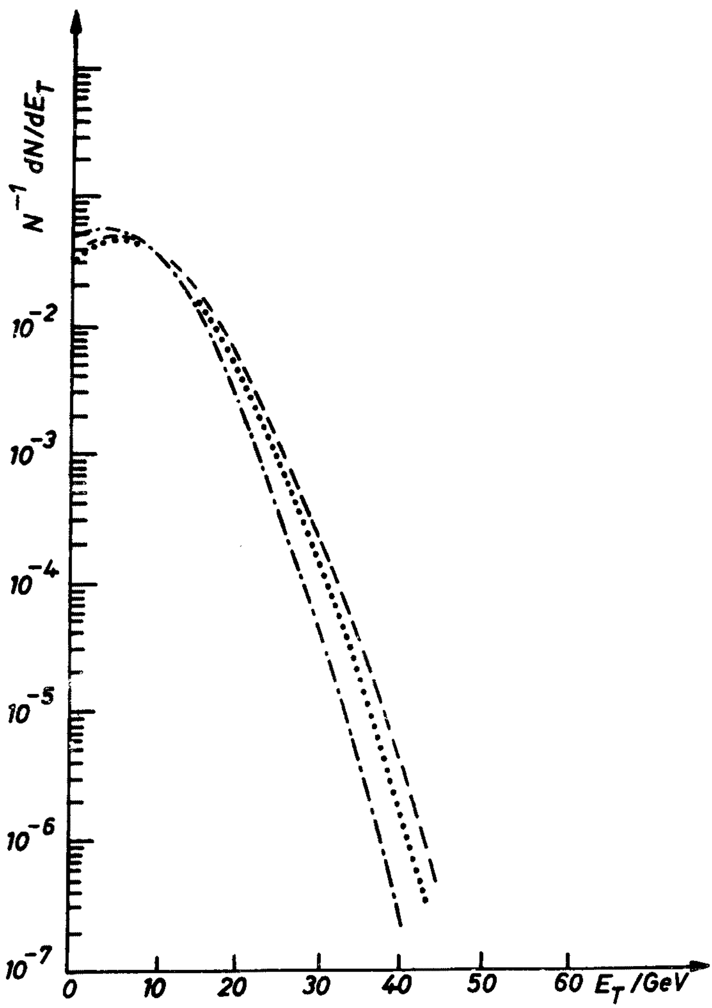

Fig. 3. E_T-distributions in pion-Pb collisions following from the model of strings attached to "wounded" nucleons: $\mu = 3$ and $\lambda_\pi = 3.33$ — dash, $\mu = 2.7$ and $\lambda_\pi = 3.67$ — dot, $\mu = 2.7$ and $\lambda_\pi = 3$ — dash-dot

Some useful formulae on compound Poisson distributions are given in the Appendix.

In Fig. 2 we compare the data [8] on E_T distributions in p-Pb collisions with a few cases of our simple model. It can be seen that the data are qualitatively well described by the model with λ_p somewhat higher than the estimated $\lambda_p \sim 3.8$. This may be caused either by little strings formed by the secondary particles within the Pb-nucleus or by the fact that a part of strings from wounded quarks did not join within the considered pseudorapidity region.

For comparison we show also the E_T-distribution corresponding to a *single* Poisson distribution with $\langle n \rangle = \lambda\mu = 15$. This distribution is manifestly too narrow what shows that a compound stochastic process is behind the data.

The HELIOS collaboration studied also the E_T-distributions in π-Pb collisions. The decrease of the number of events with increasing E_T is considerably larger than in the p-Pb case. Qualitatively this can be explained by a smaller average value of the number of produced strings. A rough estimate of λ_π based on Eq. (1) gives $\lambda_\pi \sim \frac{2}{3}\lambda_p$. The compound Poisson distributions for E_T in pion-Pb and p-Pb collisions are compared in Fig. 3.

3. *Predictions for E_T-distributions for nucleus-nucleus collisions*

In this Section we shall present a simple extension of our model to nucleus-nucleus collisions. We discuss in more detail only the ^{16}O-^{238}U collisions. We assume again that the final state hadrons are originated by the fragmentation of independent strings, that the number of strings is Poisson distributed with the expectation value λ and the number of hadron pairs coming from a particular string is again Poisson distributed with the expectation value μ. Both λ and μ depend on the rapidity interval over which the total transverse energy E_T is measured. We shall assume that this rapidity bin is the same as in the p-Pb experiment, namely $0.6 < \eta < 2.4$. The value of μ is consequently the same as above, $\mu \sim 2.7$.

The average number of strings in the target fragmentation region depends on whether we assume this number equal to a) the number of wounded nucleons in the target nucleus or b) the number of wounded quarks. To be conservative we shall make both estimates:

a) For the ^{16}O-^{238}U collision the average number of wounded nucleons in the U-nucleus is given by the formula [16, 17]

$$\langle \nu_U \rangle = \frac{238\sigma(pO)}{\sigma(OU)}, \tag{5}$$

where $\sigma(pO)$ and $\sigma(OU)$ are proton-oxygen and oxygen-uranium inelastic cross-sections. The cross-sections can be calculated by the phenomenological Bradt-Peters formula [18]

$$\sigma(AB) = \pi R_0^2[A^{1/3}+B^{1/3}-C]^2$$

with recently determined constants [19]

$$\sigma(AB) = 68.8[A^{1/3}+B^{1/3}-1.32]^2\text{mb}. \tag{6}$$

Taking $\sigma(\text{pO}) \sim 272$ mb, calculating $\sigma(\text{OU})$ from Eq. (6) and inserting the result $\sigma(\text{OU}) = 3740$ mb into Eq. (5) we obtain $\langle \nu_U \rangle \sim 17.3$.

b) The average number of wounded quarks $\langle \nu_q(\text{A}) \rangle$ in an AB collision (B — beam nucleus, A — target nucleus) has been evaluated by Białas et al. [10]. The relevant formula is

$$\langle \nu_q(\text{A}) \rangle = \frac{A\sigma(\text{pB})}{\sigma(\text{AB})} \frac{3\sigma(\text{qB})}{\sigma(\text{pB})} . \tag{7}$$

The first term in the r.h.s. gives the number of interacting nucleons in the A-nucleus, the second term is the average number of interacting quarks per one interacting nucleon. This second term has been calculated in [10] by Glauber model arguments. The resulting estimate is $\langle \nu_q(\text{U}) \rangle \sim 22$. There is still a possibility of additional short strings which may count in the target fragmentation region due either to secondary interactions or to spectator quarks. A reasonable estimate of the number of strings in this case is thus about 25.

In Fig. 4 we plot the estimated E_T-distributions for the number of strings equal to 16, 20 and 25. The lowest number corresponds to strings originated by wounded nucleons, the highest to strings originated by wounded quarks. Note the difference in scales in Figs. 2, 3 and Fig. 4.

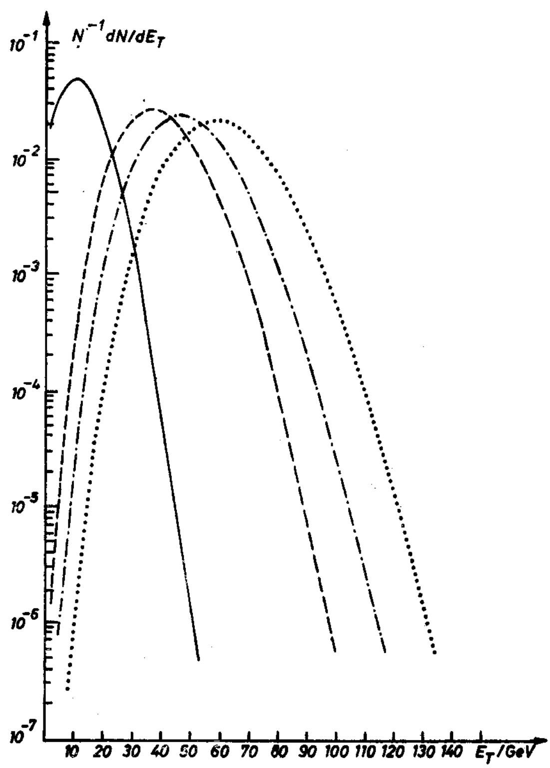

Fig. 4. Predictions for E_T-distributions in ^{16}O-^{238}U collisions. In all cases $\mu = 3$ and the effective number of strings is 16 (dash), 20 (dash-dot) and 25 (dot). The solid line gives for comparison the E_T-distribution in p-Pb collision for $\mu = 3$ and $\lambda = 5$

Two comments are in order. First, the data on E_T-distributions in O-U collisions can — if the present model is qualitatively correct — bring an evidence about whether wounded quarks or wounded nucleons are at the origin of the strings. Second, from the point of view of the plasma formation the E_T-distribution which can be described by a compound Poisson is anyway a negative evidence. Only deviations from the compound Poisson can represent a signature of plasma formation.

4. *More realistic single particle distributions*

We have assumed above that each of the secondary particles has exactly the transverse energy $\varepsilon_T = 0.4$ GeV. In this Section we shall consider more realistic transverse energy distributions for secondary particles and show that the results remain practically unchanged.

It is well known (see e.g. [20] and references quoted therein) that single particle $E = \varepsilon_T$-distributions in soft hadronic collisions are well described by the formula

$$P^{(1)}(E) = \frac{1}{T^2} e^{-E/T} E. \tag{8}$$

The factor T^{-2} is here because of the normalization, and E appears from $d^2p_T = p_T dp_T = EdE$. In order to simplify the formulae we shall consider only massless pions in the final state. The "temperature" is about 0.2 GeV since this corresponds to $\langle E \rangle = 0.4$ GeV. Consider now n-particles in the final state, each of them with the transverse energy E_i, $i = 1, 2, \ldots, n$ and probability distribution (8). The distribution of the sum of their transverse energies $E = E_1 + E_2 + \ldots + E_n$ is then given by the distribution $P^{(n)}(E)$ where

$$P^{(n)}(E) = \int P^{(1)}(E_1) \ldots P^{(1)}(E_n)\delta(E - \sum_1^n E_i) dE_1 dE_2 \ldots dE_n$$

$$= T^{-2n} e^{-E/T} \int \ldots \int E_1 \ldots E_n \delta(E - \sum_1^n E_i) dE_1 \ldots dE_n.$$

On dimensional grounds the last integral has to be proportional to E^{2n-1} and we obtain

$$p^{(n)}(E) = AT^{-2n} e^{-E/T} E^{2n-1}.$$

The constant A is determined by normalization and we finally have

$$P^{(n)}(E) = \frac{1}{T(2n-1)!} e^{-E/T} \left(\frac{E}{T}\right)^{2n-1}. \tag{9}$$

The average value of the total transverse energy is easily calculated

$$\langle E \rangle_n = 2nT \tag{10}$$

and the most probable value is $E_p = (2n-1)T$.

If we wish to approximate the distribution (9) by a Gaussian one with a mean value E_p and the width σ we can obtain σ by calculating the second derivative of (9) in the point E_p. Considering only the case of large n and using the Stirling formula $n! = \sqrt{2\pi n}\, n^n e^{-n}$ we obtain $\sigma = T\sqrt{2n-1}$. The ratio $\sigma/E_p = 1\sqrt{2n-1}$ decreases with increasing n as expected.

In Fig. 5 it is shown how the total transverse energy distribution is built up by contributions from different $2n$-particle states. Each of the $2n$-particle states has the E-distribution

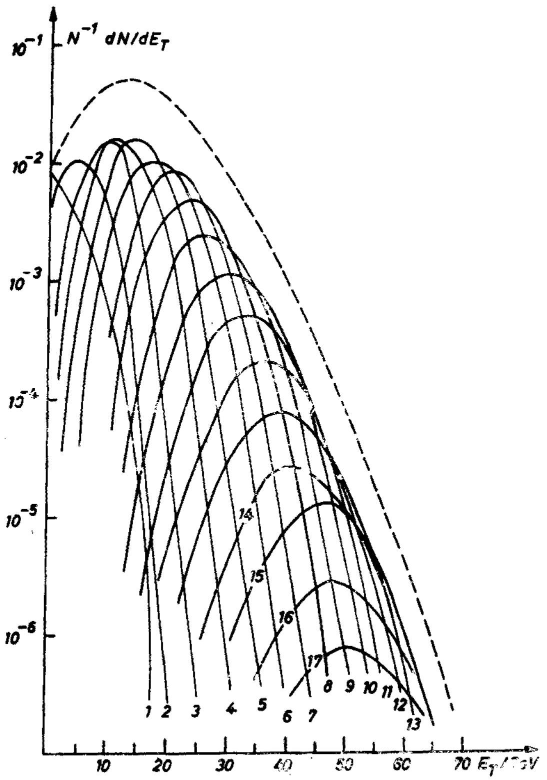

Fig. 5. The built-up of the total transverse energy distribution in p-Pb collisions from $2n$ particle states with each of the particles having the E_T-distribution (9). Dashed line — total E_T-distributions

given by Eq. (9) and is weighted by the compound Poisson probability distribution corresponding to $\mu = 3$ and $\lambda = 5$, which we have used in calculating the total transverse energy distributions in p-Pb collisions in Sect. 2. We consider only $2n$ particle states since we assume that final state particles are produced in pairs and the number of pairs in each string is Poisson distributed (Sect. 2). The sum of various $2n$ particle distributions is practically the same as the corresponding curves in Sect. 2, which were obtained by drawing a smooth line through points at multiples of 0.8 GeV.

5. *Comments and conclusions*

The transverse energy distributions calculated in the present simple model correspond to a picture in which a heavy ion collision is considered in a sense as a sum of nucleon--nucleon or quark-quark collisions. No plasma formation is assumed. This picture leads to transverse energy distributions given by a compound stochastic process, the compound Poisson being the most natural option. From this point of view only deviations from a compound Poisson distribution can represent a signature of plasma formation. We shall now perform a simple estimate of when the plasma can be formed and how this will influence the shape of the E_T-distribution.

The energy density in a single string as formed in a nucleon-nucleon collision can be estimated as follows: suppose that about three hadrons, each with the energy of about 0.4 GeV are produced per rapidity unit and that they are materialized when the rapidity unit extends over a cylinder with length of about 1 fm. The radius of a cylinder R can be taken as $R \sim 1$ fm. The energy density is

$$\varepsilon \sim \frac{1.2 \text{ GeV}}{(\pi R^2)(1 \text{ fm})} \sim 0.38 \text{ GeV fm}^{-3}.$$

If there are n strings formed in an O-U collision the energy density will be

$$\varepsilon' \sim n \frac{\varepsilon}{16^{2/3}} = \frac{n\varepsilon}{6.3},$$

where we have assumed that the strings are formed in a cylinder with a radius of $A^{1/3}R$. The energy density of 3 GeV fm^{-3} is reached for $n \sim 50$.

Suppose now that in the experiment one obtains the data on the E-distribution which correspond to the number of $n > n_{crit}$ (at n_{crit} the energy density of overlapping strings reaches the limit for plasma formation). How will the transverse energy distribution look like in this region? As argued by several authors [20–23] the plasma formation will manifest itself by the increase of $\langle p_T \rangle$ per particle and the increase of the single particle transverse energy will be seen as an increase in the total transverse energy. The signature for plasma formation would be a change in the slope of the E_T-distribution as qualitatively indicated in Fig. 6. In conjunction with that, one would also expect other plasma signatures to appear, like an increase in the strange particle and dilepton production [24–27]. The appearance of all these signals at the same time could be a convincing evidence of plasma formation.

Since it is rather uncertain at which value of the transverse energy the deviations from a compound stochastic process start, it is most desirable to study the E_T-distributions to highest possible values of E_T.

The preceding scenario is probably an oversimplification. To obtain the energy density of about 3 GeV fm^{-3} over the *whole* cross-section of the O-nucleus one needs about fifty strings. To reach this energy only over a part of this cross-section is easier. Suppose that the position of a string is a random variable. The probability p that the çentre of the string

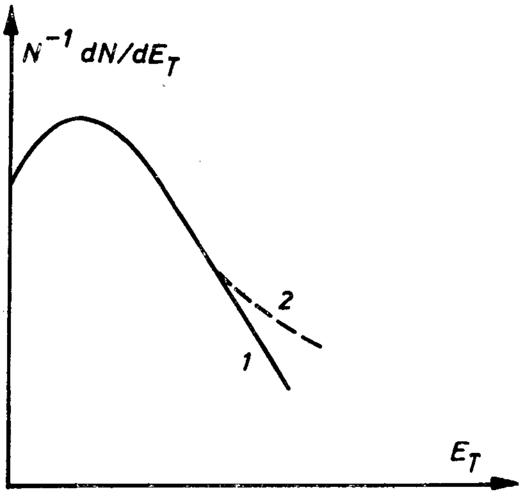

Fig. 6. A qualitative indication of plasma formation. *1* — compound Poisson distribution, *2* — deviation from the compound Poisson. Because of uncertainties in estimating E_T at which the deviation starts we do not give scale

is within the area of πfm^2 of the whole $\pi A^{2/3}\, \text{fm}^2$ is

$$p \sim \frac{\pi}{\pi A^{2/3}} \sim \frac{1}{6.3}\,.$$

If the total number of strings is N the probability p' to have more than $(n-1)$ strings within a specified area of πfm^2 is

$$p' = \sum_{k=n}^{N} \binom{N}{k} p^k (1-p)^{N-k}.$$

So far as $p' \ll 1$ we can estimate in this way also the probability to have more than $(n-1)$ strings in any area of size πfm^2. We obtain

$$\tilde{P}(N) \doteq \frac{1}{p} \sum_{k=n}^{N} \binom{N}{k} p^k (1-p)^{N-k}, \quad \text{for} \quad \tilde{P}(N) \ll 1.$$

For $\tilde{P}(N)$ larger, say for $\tilde{P}(N) > 0.1$ we have to calculate $\tilde{P}(N)$ starting with multinomial distribution [28]. The function $\tilde{P}(N)$ reaches 1 for N corresponding to the average string density equal to n.

The probability $\tilde{P}(N)$ is plotted as a function of $E_T = 2.4\, N$ GeV in Fig. 7 (we assume that each string contributes 2.4 GeV to the total transverse energy within $0.6 < \eta < 2.4$).

This scenario is perhaps more realistic than the preceding one. A bad point about it is that the deviation from E_T-distributions corresponding to a simple compound Poisson

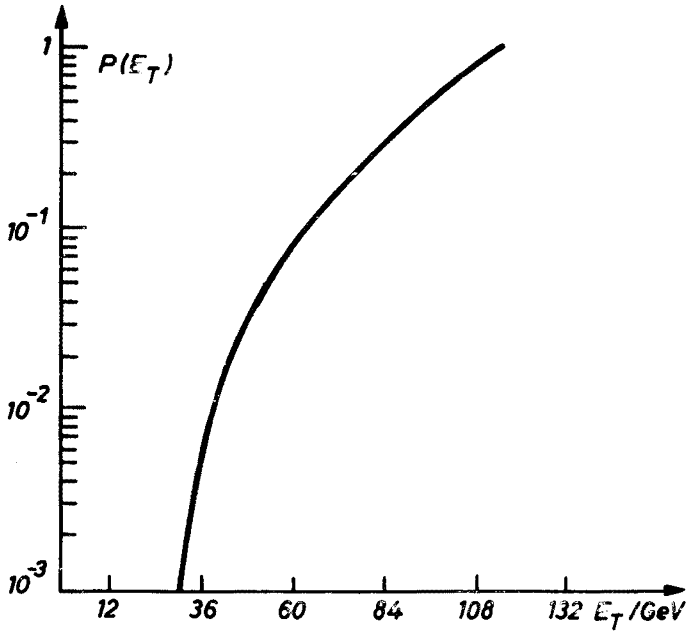

Fig. 7. The probability for reaching energy density larger than 3 GeV fm^{-3} within a tube of cross-section 1 fm^2 as a function of $E_T = 2.4$ GeV N, where N represents the number of strings in a given event

will not be abrupt like in Fig. 6 but smoother. In such a situation it will be even more important to measure also other plasma signatures (e/π, e^+e^-/π and K/π ratios) together with the E_T-distribution.

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APPENDIX

We shall gather here some formulae which are useful for calculating probabilities according to the compound Poisson distribution defined by Eqs (2), (3) and (4). One possibility is to use the formula (obtained via probability generating functions [28])

$$P(n) = \left[\sum_{r=0}^{n} v_r^{(n)}\right] \exp\left[\lambda(e^{-\mu}-1)\right], \tag{A1}$$

where $v_r^{(n)}$ are obtained by recurrent relations

$$v_r^{(n)} = \frac{r\mu}{n} v_r^{(n-1)} + \frac{\lambda\mu e^{-\mu}}{n} v_{r-1}^{(n-1)}, \qquad r = 0, \ldots, n$$

$$v_0^{(0)} = 1, \quad v_r^{(n)} = 0 \quad \text{for} \quad r < 0 \quad \text{or} \quad r > n.$$

Another possibility is to procede in the following way. The sum of two Poisson distributed quantities with expectation values μ_1 and μ_2 is again Poisson distributed with the expectation value $\mu_1+\mu_2$ [28]. The sum of N Poisson distributed quantities, each with the expectation value μ will be Poisson distributed with the expectation value $N\mu$. The probability to produce n hadron pairs from N strings becomes

$$P_N(n) = \frac{(N\mu)^n}{n!} e^{-N\mu}.$$

Since the probability to produce N strings is again Poissonian (3) we have finally

$$P(n) = \sum_{N=0}^{\infty} \frac{\lambda^N e^{-\lambda}}{N!} \frac{(N\mu)^n}{n!} e^{-N\mu}$$

$$= \frac{\mu^n}{n!} e^{-\lambda} \sum_{N=0}^{\infty} \frac{\lambda^N}{N!} N^n e^{-N\mu}.$$

In evaluating the contribution from large N's one can use the Stirling formula.

Note added in proof. The Poisson distribution in the number of wounded nucleons is a reasonable approximation for the large transverse energy tail of a pA interaction. This approximation is however rather inaccurate for nucleus-nucleus interactions where the distribution of wounded nucleons is essentially given by the geometry of overlapping nuclei. As a consequence distributions of the number of wounded nucleons are broader than Poisson distribution. The topic is discussed more realistically in J. Ftáčnik, K. Kajantie, N. Pišútová and J. Pišút: On the transverse energy distributions in the central rapidity region of O-Pb collisions at 200 GeV per nucleon (Bratislava preprint, to be published in *Phys. Lett.* **B** 1987).

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