Possible Manifestation of Quark-Gluon Plasma in Multiplicity Distributions from High-Energy Reactions

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We show that in order to explain the observed dependence of multiplicity distributions on energy and shifts of the centers of rapidity bins it is sufficient to assume the existence of two sources. One source is concentrated at small rapidities and has properties of a thermally equilibrated system as could be expected from a quark-gluon plasma. The other one, contributing to the whole rapidity region, displays characteristics of bremsstrahlung emission.

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The search for the quark-gluon plasma (QGP) is in the center of interest of strong-interaction physics at high energies. While heavy-ion reactions may provide a way to obtain this new state of matter in the laboratory, this approach is by far not the only one possible. Indeed, already before the establishment of a heavy-ion "industry," it had been advocated[1] that hadronic reactions, too, provide interesting information about QGP. In this Letter, we present new evidence, based upon multiplicity distributions, which supports this point of view. We show that a consistent picture of multiparticle (nondiffractive) phenomenology emerges if one assumes that in multiproduction processes there are two types of sources: One of them gives rise to a negative-binomial multiplicity distribution $P_1(n_1)$, while the other one follows a Poisson distribution $P_2(n_2)$. This assumption is enough to provide a description of the multiplicity distributions in the whole rapidity range as well as in restricted rapidity windows, and their dependence on energy and on the position of the rapidity bins.[2] We further assume as a first approximation that the partition of energy between the two sources is independent of the total energy available for particle production $W=K\sqrt{s}$, where K is the inelasticity. Thus $W=W_1+W_2$, where W_1 and W_2 are the energy contents of the two sources. The data then reveal a very striking behavior for these two subsystems: The first is concentrated at small rapidities y and its mean multiplicity $\langle n_1\rangle$ behaves like $W^{1/4}$; the second populates mainly large y and its mean multiplicity $\langle n_2\rangle$ behaves like $\ln s$.

The first dependence is what one would expect from a thermally equilibrated source with an equation of state in which pressure is equal to one third of the energy density; a QGP is expected to satisfy such an equation of state (see Carruthers[3]). The second dependence is again what one would expect, this time from a coherent emission mechanism. Furthermore, a rather generally accepted picture of hadronic collisions in terms of quarks and gluons[4–6] asserts that in each event there are leading particles due to the throughgoing quarks and a central blob formed by the interacting gluons. It has been shown very recently[7] that such a model can explain not only the leading-particle effect, but also reproduces the inelasticity distribution and its energy dependence. A straightfoward and most natural extension of this model is the assumption that the throughgoing quarks independently radiate gluons, part of which hadronize directly. If the hadronization process does not change the form of the gluon multiplicity distribution, $P_2(n_2)$ can then be assumed to be Poisson-type. The rest of the gluons, as well as the primordial gluons, presumably equilibrate. This component is most naturally described by a thermal (e.g., negative-binomial) distribution.

We write the total multiplicity as

$$n=n_1+n_2, \tag{1}$$

and $P(n)$ as a convolution

$$P(n)=\sum_{n_1+n_2=n} P_1(n_1)P_2(n_2), \tag{2}$$

with $P_1(n_1,\langle n_1\rangle)$ given by the generalized Bose-Einstein (negative-binomial) distribution with k cells,

$$P_1(n_1,\langle n_1\rangle)=[(n_1+k-1)!/n_1!(k-1)!][k/(\langle n_1\rangle+k)]^k[\langle n_1\rangle/(\langle n_1\rangle+k)]^{n_1}, \tag{3}$$

and $P_2(n_2,\langle n_2\rangle)$ of Poisson shape,

$$P_2(n_2,\langle n_2\rangle)=e^{-\langle n_2\rangle}\langle n_2\rangle^{n_2}/n_2!. \tag{4}$$

We then have three parameters which characterize our system, viz., $\langle n\rangle$, k, and $\tilde{p}\equiv\langle n_1\rangle/\langle n\rangle$. In quan-

TABLE I. Comparison of two-component model distributions with experimental data at $\sqrt{s}=52.6$ GeV (CERN ISR, Ref.13) and $\sqrt{s}=540$ GeV (CERN $p\bar{p}$ collider $Sp\bar{p}S$, Ref. 14) with $\tilde{p}$ estimated from Eq. (5). For compactness of presentation, as well as in order to minimize the influence of bin-to-bin correlations, the probabilities (given as percentages) for observation of n particles have been grouped in multiplicity intervals ($\Delta n=3$ at 52.6 GeV, $\Delta n=6$ at 540 GeV). The theoretical probabilities have been computed with k fixed at either 1 or 2. Of the corresponding χ^2 values, the first line includes the lowest-multiplicity bin (Ref. 15), while the second one has this bin excluded (Ref. 16). Note that two constraints (viz., $\langle n\rangle$ and $\tilde{p}$ estimated) affect the number of degrees of freedom.

$\sqrt{s}=52.6$ GeV				$\sqrt{s}=540$ GeV			
n^-	$P_{\rm expt}$	$P_{\rm theor}$ $k=1$	$P_{\rm theor}$ $k=2$	n^-	$P_{\rm expt}$	$P_{\rm theor}$ $k=1$	$P_{\rm theor}$ $k=2$
0–2	15.53 ±1.21	14.02	14.58	0–5	14.37 ±0.42	9.66	12.86
3–5	41.50 ±2.13	43.38	42.85	6–11	34.60 ±0.73	41.74	36.80
6–8	28.99 ±0.91	29.00	29.00	12–17	25.80 ±0.58	26.85	26.69
9–11	10.73 ±0.49	9.66	10.14	18–23	14.70 ±0.49	12.08	13.56
12–14	2.50 ±0.25	2.58	2.65	24–29	6.50 ±0.24	5.37	6.02
15–20	0.75 ±0.17	0.83	0.74	30–35	2.85 ±0.18	2.39	2.49
				36–41	0.87 ±0.11	1.06	0.98
				42–51	0.39 ±0.07	0.63	0.49
	χ^2 (4 dof)	7.8	2.8		χ^2 (6 dof)	299.6	41.1
	χ^2 (3 dof)	6.3	2.2		χ^2 (5 dof)	173.4	28.1

tum statistics (QS), a negative binomial corresponds to a purely chaotic source with k cells and a Poisson distribution to a purely coherent one. The parameter $\tilde{p}$ is then the effective amount of chaos and $1-\tilde{p}$ the amount of coherence of the system. In this interpretation, k is an integer and represents the number of independent quantum states (e.g., charges). Note that the effective measure of chaos $\tilde{p}$ introduced here differs from the measure of chaos used in one-component QS approaches,[8,9] where coherent and chaotic amplitudes (rather than probabilities) are added. The need for a convolution [Eq. (2)] arises because of the dependence of the effective $\tilde{p}$ on the shifts of centers of rapidity windows. It was argued by Fowler and Weiner[10] that the parameters of QS distributions should not depend on rapidity, and therefore the generalization represented by Eq. (2) seems necessary.

Now we proceed to apply this formalism to experimental data. We estimate $\tilde{p}$ for various k from the second normalized moment $C_2=\langle n^2\rangle/\langle n\rangle^2$ of the multiplicity distribution:

$$\tilde{p}=[k(C_2-1-1/\langle n\rangle)]^{1/2}, \quad (5)$$

and then calculate the distribution $P(n)$ using Eqs. (2)–(4).[11] By doing this at various energies, we get the energy dependence of $\tilde{p}$ and hence $\langle n_1\rangle(W_1)$ and $\langle n_2\rangle(W_2)$.

Finally, by consideration of the data for various positions of the centers η_c of the pseudorapidity bins, the rapidity dependence of $\langle n_1\rangle$ and $\langle n_2\rangle$ can be determined. It is important to mention that the possibility of using the same mathematical form for $P_1(n_1)$ and $P_2(n_2)$ both for the total rapidity range and for narrow η windows is given only for the class of "reproducible" distributions to which the negative binomial and the Poisson distributions belong.[12] The results are represented in Table I and Figs. 1 and 2, and they

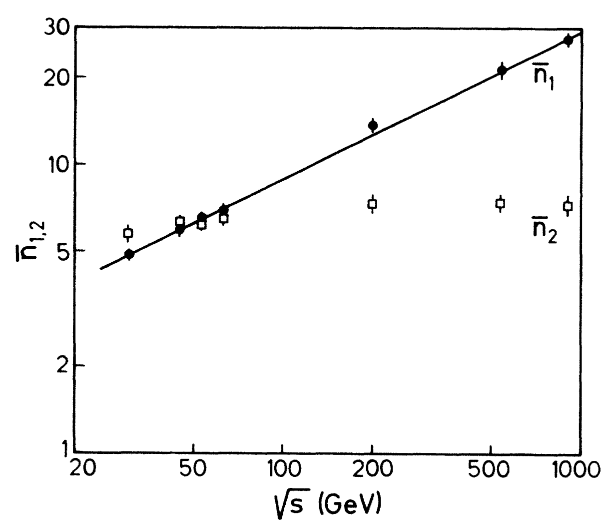

FIG. 1. Dependence of the estimated mean multiplicities $\langle n_1\rangle$ and $\langle n_2\rangle$ of the two components on $\sqrt{s}$. The chaotic component $\langle n_1\rangle$ is represented by circles; the coherent component $\langle n_2\rangle$ (squares) is shown here on the same log-log scale as $\langle n_1\rangle$ for the sake of comparison. $\sqrt{s}$ is expressed in gigaelectronvolts. The C_2 moments needed to estimate $\tilde{p}$ were taken from Ref. 17. The s dependences of $\langle n_1\rangle$ and $\langle n_2\rangle$ are similar to those on W_1 and W_2, respectively, because of the weak s dependence of the inelasticity and because of the assumption of constant partition of W into W_1 and W_2.

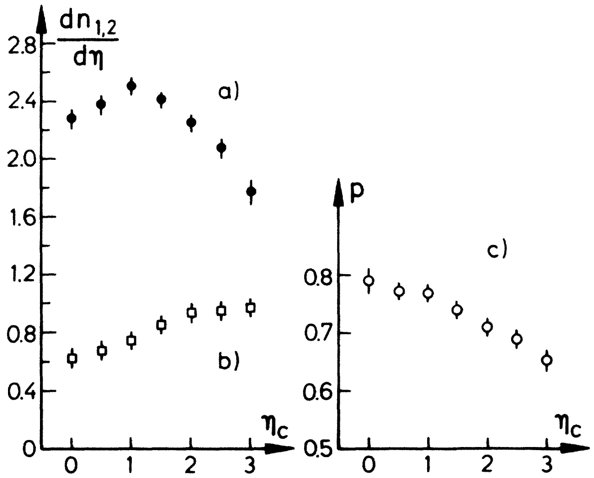

FIG. 2. (a),(b) Dependence of the estimated values of $\langle n_1 \rangle$ and $\langle n_2 \rangle$ on the center η_c of pseudorapidity windows each 0.4 units wide. (c) Dependence of the effective measure of chaos $\tilde{p}$ on η_c. The C_2 moments used to evaluate $\tilde{p}$ come from Ref. 18, with use of nonoverlapping windows in order to ensure statistical independence of the moments.

show the following.

(1) At fixed s the multiplicity distributions $P(n)$ calculated from our theoretical expressions (2)–(4) with $\tilde{p}$ determined from the second moment [Eq. (5)] are in reasonable agreement with the experimental values.

(2) The effective measure of chaos $\tilde{p}$ increases with $\sqrt{s}$ from $\simeq 40\%$ at $\sqrt{s}=30$ GeV to $\simeq 80\%$ at $\sqrt{s}=900$ GeV. This conclusion is in qualitative agreement with the result of Ref. 8, where a QS approach with a partially coherent single source was found to account for the multiplicity distributions, provided that the corresponding measure of chaos also increases with energy.

(3) The mean of the chaotic component $\langle n_1 \rangle$ increases with its available energy W_1 like W_1^α with α close to $\frac{1}{2}$, while the coherent one behaves like $\ln W_2$. A more precise determination of α is not possible until more accurate information about the inelasticity becomes available.

(4) At 540 GeV, the negative binomial source [Fig. 2(a)] is concentrated at low rapidities and has a shape very reminiscent of the predictions of Landau's hydrodynamical model.[19] The Poisson component [Fig. 2(b)] extends over the entire η range, although it contributes more to large η, as one would expect, e.g., from a bremsstrahlung mechanism. Another way of expressing these last findings is to note that the measure of chaos $\tilde{p}$ decreases with the shift of the center η_c of the rapidity window from $\tilde{p}=0.75$ at $\eta_c=1$ to $\tilde{p}=0.63$ at $\eta_c=3$ [Fig. 2(c)]. This thus confirms an earlier observation[20] concerning proton emulsion data at $\sqrt{s}=20$ GeV where, as far as we can gather, the first measurement of multiplicity distributions in different rapidity windows was suggested and performed, and where the important implications of this effect for the understanding of nuclear transparency were stressed ("self-induced transparency"). Although other two-component models have been proposed,[21] none of them addresses, proves, and exploits the effects discussed here.

(5) The number of independent quantum states k turns out to be $k=1$ for the shifted rapidity bins [Eq. (5) has unphysical solutions $\tilde{p}>1$, for $k>1$]. On the other hand, for the total rapidity region the χ^2 analysis suggests a value $k=2$, although the case $k=1$ cannot be excluded (at least at $\sqrt{s}=52.6$ GeV). If k is interpreted as the number of independent charge states, this suggests that we have local charge conservation in the different rapidity windows, while in the full rapidity range the positive and negative charges appear (as is to be expected) to be produced independently.

In the present approach, the forms for P_1 and P_2 are two extremes of QS distributions (completely chaotic and completely coherent). The dependences of $\langle n_1 \rangle$ and $\langle n_2 \rangle$ on y (or η) suggest that we are dealing with two sources, one in the center corresponding to the interacting gluons from projectile and target, while the other one corresponds to projectile and target fragmentation. Finally, the $W_1^{1/2}$ and $\ln(W_2)$ behaviors of $\langle n_1 \rangle$ and $\langle n_2 \rangle$ are consistent with an interpretation of the first source in terms of a thermally equilibrated system (QGP?) and of the second source as due to a bremsstrahlung mechanism. The well-known fact that at low energies a logarithmic dependence on s of the mean multiplicity is consistent with the data, while at high energies a stronger s dependence is observed, thus gets a natural explanation.

The model suggested here is an oversimplification. Among other things, the role of a finite correlation length in rapidity[10] as well as the fluctuation in the energy partition between the two sources (i.e., in $\tilde{p}$) have been ignored. However, preliminary estimates of these effects suggest that the qualitative conclusions obtained here are not altered. These conclusions can be summarized as follows.

(1) The mean multiplicity at small rapidities increases with energy much faster than at large rapidities, suggesting the existence of two physically separated sources.

(2) The central source is predominantly chaotic (thermal?)[22] while the peripheral one could be viewed as essentially coherent.

(3) The relative amount of chaos increases sharply with energy. This is in agreement with the conclusions of Fowler *et al.*,[23] where a single-source QS formalism with inclusion of the finiteness of the rapidity correlation length was applied to the global multiplicity distri-

butions and forward-backward correlations. If we add the observed[23] dramatic increase with energy of the correlation length, these facts hint at a possible approach to a phase transition. In particular, the central source with its $W_1^{1/2}$ dependence is a most natural candidate for the expected QGP. To check this possibility, the whole arsenal of "signals" developed for the field of QGP could be applied to this kinematical region, although the heuristic value of such signals is an open question.

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[1]Compare, e.g., *Local Equilibrium in Strong Interaction Physics*, edited by D. K. Scott and R. M. Weiner (World Scientific, Singapore, 1985); *Quark Matter '84*, edited by K. Kajantie, Lecture Notes in Physics Vol. 221 (Springer, New York, 1985).

[2]It should be pointed out that multiplicity distributions recorded in nonoverlapping rapidity windows have the advantage of providing physical information without the need for explicit multiparticle correlations. This is not the case for distributions in rapidity bins of different widths with a common center.

[3]P. Carruthers, Phys. Rev. Lett. **50**, 1179 (1983); see also Ref. 1.

[4]L. van Hove and S. Pokorski, Nucl. Phys. **B86**, 243 (1975).

[5]E. V. Shuryak, Phys. Rep. **61C**, 71 (1980).

[6]P. Carruthers and Minh Duong-Van, Phys. Rev. D **28**, 130 (1983).

[7]G. N. Fowler, R. M. Weiner, and G. Wilk, Phys. Rev. Lett. **55**, 173 (1985).

[8]G. N. Fowler, E. M. Friedlander, R. M. Weiner, and G. Wilk, Phys. Rev. Lett. **56**, 14 (1986).

[9]P. Carruthers, Los Alamos National Laboratory Report No. LA-UR-86-1540, 1986 (to be published).

[10]G. N. Fowler and R. M. Weiner, Phys. Rev. D **14**, 3118 (1978).

[11]In applying this formalism to experimental data, one should take into account this inelasticity distribution (Ref. 7). This has been done by correction of Eq. (5) as discussed in Ref. 8; the final results presented in Figs. 1 and 2 contain these corrections. In deriving the energy dependence of $\langle n_1 \rangle$ and $\langle n_1 \rangle$, we took into account the change of inelasticity with $\sqrt{s}$ (Ref. 7). However, in order to simplify the presentation of the multiplicity distributions shown in Table I, a constant inelasticity was assumed for this case. We have checked that the inclusion of this effect does not spoil the agreement with experiment.

[12]"Reproducible" means that a binomial sampling from such a distribution leads to a distribution of the same shape but with different parameters.

[13]A. Breakstone *et al.*, Phys. Rev. D **30**, 528 (1984).

[14]B. Asman, University of Stockholm Report No. 85-17, 1985 (unpublished).

[15]Events with very low multiplicities ($n < 3$ at the CERN Intersecting Storage Rings, $n < 5$ at the CERN $p\bar{p}$ collider $Sp\bar{p}S$) can be (and often are) contaminated by imperfections in exclusion of single diffractive events.

[16]The large values of χ^2 for the UA5 data are most likely connected with the fact that the errors of Ref. 14 are of purely statistical origin (compare the errors at 52.6 GeV which were obtained with considerably higher statistics).

[17]G. J. Alner *et al.* (UA Collaboration), Phys. Lett. **160B**, 199 (1985).

[18]G. J. Alner *et al.* (UA5 Collaboration), CERN Report No. EP-85-61, 1985 (unpublished).

[19]K. Wehrberger and R. M. Weiner, Phys. Rev. D **31**, 222 (1985).

[20]G. N. Fowler, E. M. Friedlander, and R. M. Weiner, Phys. Lett. **104B**, 239 (1981); cf. especially Fig. 2 for events with $N_h = 0, 1$ which are dominated by p-p collisions.

[21]H. Bannerjee, T. De, and D. Syam, Nuovo Cimento **89A**, 353 (1985); Cai Xu *et al.*, Phys. Rev. D **33**, 1287 (1986).

[22]Its thermal character is suggested not only by its chaoticity and the Landau-model-like shape of its rapidity distribution, but also by the well-known exponential shape of the transverse momentum distributions.

[23]G. N. Fowler, E. M. Friedlander, R. M. Weiner, and G. Wilk, "Quantum Statistical Connection between Forward-Backward Correlations and Multiplicity Distributions and its Striking Consequences," to be published.