Rapidity dispersion and cluster production in 67-GeV/c p-N interactions

N. S. Arya, D. P. Goyal, A. Mozumder, P. K. Sengupta, and S. Singh
Department of Physics and Astrophysics, University of Delhi, Delhi-110007, India
(Received 8 October 1979)

The p-N interactions in emulsion at 67 GeV/c have been analyzed in terms of the distributions of rapidity and rapidity dispersion. The study of the dispersion parameter from individual events reveals significant clusterization amongst the final-state particles. Moreover, the nature of clusterization in the nondiffractive region of the rapidity space seems to be independent of charged-particle multiplicity of the event. This fact has been employed to estimate the mass and number of particles constituting the cluster which are found to be $\simeq 2.1$ GeV and $\simeq 6$, respectively.

I. INTRODUCTION

The small-transverse-momentum property and the leading-particle effect have, for a long time, been known as distinct features of the high-energy interactions. Recent work has further revealed that at energies $\gtrsim 50$ GeV, the existence of two-particle correlations may be treated as another salient feature of high-energy phenomena. The magnitude of the well-known correlation parameter f_2, obtained from the overall charged-prong cross sections, is a simple indicator of such correlations. For energies $\gtrsim 60$ GeV this parameter is observed to become increasingly positive suggesting the presence of two-particle positive correlations at least at the inclusive level. Therefore, it must be investigated as to what extent this correlation is true of individual events.

In the past, most of the correlation studies have been confined to the inclusive distributions of rapidity, rapidity gap, or two-particle correlation parameter. It may be emphasized here that in such distributions [for example, in the inclusive distribution of the type $(1/N)dn/dy$] the contribution to each bin comes from all the particles produced in different events with a given multiplicity. This complicates the analysis. On the other hand, correlation at the level of individual events can be easily studied through the rapidity-dispersion parameter δ. Such a study has the advantage that the nature of the distribution obtained reflects the kinematic features not of individual particles, but of the event, taken as a whole. In this sense the dispersion analysis is more informative.

Berger *et al.*[1] have claimed this parameter (δ) to be a quantitative measure of clusterization in individual events and several authors[2,3] have made use of this approach to analyze the high-energy data in the energy range 100 to 400 GeV. Below 100 GeV there is only one such study[4] at 40 GeV. Apparent clustering, attributable to energy-momentum restrictions, has been reported[5] even for interactions having primary energy $\lesssim 30$ GeV. Hence, it is desirable to measure the clusterization effects in the (40–100) GeV energy range.

In the present work, we have studied the rapidity dispersion of charged particles produced in 67-GeV/c p-N interactions in emulsion. The analysis reveals significant clusterization of secondary particles and provides an alternative method for the estimation of the mean cluster density and size and mass of the clusters. A comparison of these cluster parameters with those obtained at higher energies reveals that the mass and size of the cluster remain practically independent of energy.

II. EXPERIMENTAL DETAILS

The present work is based on a line-scan sample of proton-nucleon interactions obtained by the AADCLMTUB collaboration[6] in a NIKFI-emulsion stack exposed to a beam of 67-GeV/c protons from the Serpukhov accelerator. The effective proton-nucleon interactions in emulsion were selected by employing the following well-known selection criteria:

(i) The event must have either no heavy track ($N_h = 0$) associated with it or at best it may have one grey track ($N_g = 1$) emitted in the forward direction in the laboratory system (LS).

(ii) There must be no Auger electron or recoil nucleus associated with the event.

Further, since this study is mainly concerned with the analysis of the dispersion of the rapidity distribution in individual events both with and without the leading particle, we have selected only those events which have a number of charged particles $n_s \geq 4$.

The number of events satisfying these selection criteria is found to be 801, contributing a total of 5854 charged particles.

The longitudinal rapidity of a secondary particle in an event in the LS is defined to be

$$y = \tfrac{1}{2} \ln[(E + p_{\parallel})/(E - p_{\parallel})], \tag{1}$$

where E is the energy and $p_{\parallel}$ is the component of the momentum of the secondary particle parallel to the direction of the primary particle. Therefore, the calculation of y requires a knowledge of the mass (m), momentum (p), and the emission angle (θ) of the particle. It is well known that at high energies ($\gtrsim 50$ GeV), it is not possible to measure the momentum of a secondary particle accurately; therefore, one generally employs the approximation

$$E \simeq p , \tag{2}$$

which holds reasonably well for most of the secondary particles (~80% of which are pions). Under this approximation, Eq. (1) reduces to

$$y \approx \eta = -\ln \tan(\theta/2) , \tag{3}$$

where η is known as the pseudorapidity. Thus, η is a good estimate of y. Therefore, we have employed η instead of y, of each charged particle for the present study.

III. RESULTS AND DISCUSSION

A. Dispersion analysis

If in individual events, the final-state particles are emitted in the form of clusters, they tend to have significant correlations (more than those expected from pure kinematic constraints). The cluster constituents are quite closely spaced about the direction of emission of the cluster; therefore, their rapidity dispersion is expected to be small.

The dispersion parameter for an event having n_s charged particles is defined as

$$\delta = \left[\frac{1}{(n_s - 1)} \sum_{i=1}^{n_s} (y_i - \bar{y})^2\right]^{1/2} , \tag{4}$$

where y_i and $\bar{y}$ are, respectively, the ith particle rapidity and the mean rapidity of the event.

The bulk of the secondary particles are emitted in the central region of rapidity space; therefore, it is also interesting to investigate the effect of the leading particle on the value of δ. We define the leading particle in an event as that extreme particle for which $|y_i - \bar{y}|$ is maximum in that event. Excluding this value of rapidity, we recalculate mean rapidity for $n_s - 1$ particles and denote it by $\bar{y}^1$, then the corresponding dispersion δ^1 is given by

$$\delta^1 = \left[\frac{1}{(n_s - 2)} \sum_{i=1}^{n_s - 1} (y_i - \bar{y}^1)^2\right]^{1/2} . \tag{5}$$

Another useful parameter in the dispersion analysis is the dispersion of dispersion (w). If δ or δ^1 is a measure of clusterization, w is a measure of fluctuations in the cluster width in rapidity space. At a fixed energy, we may study w as a function of multiplicity of the event. Then, if N is the number of events for given multiplicity, we define w and w^1 corresponding to δ and δ^1, respectively, by the following equations:

$$w = \left[\frac{1}{(N - 1)} \sum_{i=1}^{N} (\delta_i - \bar{\delta})^2\right]^{1/2} \tag{6}$$

and

$$w^1 = \left[\frac{1}{(N - 1)} \sum_{i=1}^{N} (\delta_i^1 - \bar{\delta}^1)^2\right]^{1/2} , \tag{7}$$

where $\bar{\delta}$ and $\bar{\delta}^1$ are the average values of δ and δ^1 for the multiplicity under consideration.

For the present data, the values of $\bar{\delta}$, $\bar{\delta}^1$, w, and w^1 have been shown in Table I for different multiplicities. These values indicate that there is a sudden transition in the values of the parameters in going from low-multiplicity (≤ 6) to high-multiplicity (≥ 7) events. The first and the second groups contain events having multiplicities lower and higher than the average multiplicity (6.2), respectively. It seems that the dominant mechanism of particle production may be different for the two groups.

Figure 1 shows the δ and δ^1 distribution for pp-type events having different multiplicities at 67 GeV. It is observed that the former distributions are always broader than the latter ones. The modal values of δ^1 distributions are less than those of δ distributions. These trends are more clearly revealed by the low-multiplicity events ($n_s = 4$ to 6). Similar features were observed at primary energies 40 (Ref. 4), 303 (Ref. 2), and 400 GeV (Ref. 3).

Figure 2 shows the variation of $\bar{\delta}$ and $\bar{\delta}^1$ with multiplicity. The data at 40 and 303 GeV are also shown for comparison. The points at 303 GeV are based on projected angles. It is seen that δ decreases with multiplicity, but the rate of fall is larger at smaller multiplicities (≤ 6). The trends at all the three energies are similar. However, the interesting observation is that the removal of the leading particle has made the variation of rapidity dispersion significantly slow and $\bar{\delta}^1$ may be taken as almost independent of multiplicity with the exception of the $\bar{\delta}^1$ value for $n_s = 4$, which seems to be a bit smaller. This may be due to the fact that at low multiplicities the apparent correlation effects due to kinematic constraints become significant vis a vis true clusterization effects. However, the multiplicity independence of $\bar{\delta}^1$ for $n_s > 4$ clearly indicates that the nature of clusterization at different multiplicities remains the same. This implies that the fundamental cluster parameters, such as cluster mass and cluster size, may also

TABLE I. The values of dispersion parameters for different multiplicities at 67 GeV.

Multiplicity (n_s)	$\bar{\delta}$	$\bar{\delta}^1$	w	w^1
4	1.46	0.78	0.60	0.52
5	1.15	0.76	0.48	0.41
6	1.29	0.87	0.41	0.35
4 to 6	1.30 ± 0.03	0.81 ± 0.02	0.58 ± 0.02	0.43 ± 0.02
7	1.16	0.89	0.33	0.27
8	1.14	0.88	0.32	0.32
9	1.19	0.95	0.28	0.26
10	1.09	0.90	0.29	0.27
11	1.24	1.01	0.26	0.26
12	1.10	0.93	0.27	0.21
13	1.01	0.85	0.26	0.25
14	1.08	0.92	0.13	0.14
15	0.89	0.78	0.24	0.20
7 to 15	1.13 ± 0.02	0.90 ± 0.01	0.31 ± 0.01	0.28 ± 0.01

be independent of multiplicity.

Berger *et al.*[1] have suggested that events having $\delta^1 \leqslant 0.9$ correspond to production of single isotropically decaying cluster (also called nova). At sufficiently low energies ($\lesssim 30$ GeV) most events necessarily give $\delta^1 \leqslant 0.9$, which is attributable to the energy-momentum constraints. The nova model predicts[1] that the population of events having $\delta^1 \leqslant 0.9$ should decrease with energy. In the present experiment the number of such events is 58%, and at 303 and 400 GeV this number is found[3] to be 39% and 30%, respectively, which is consistent with the nova model.

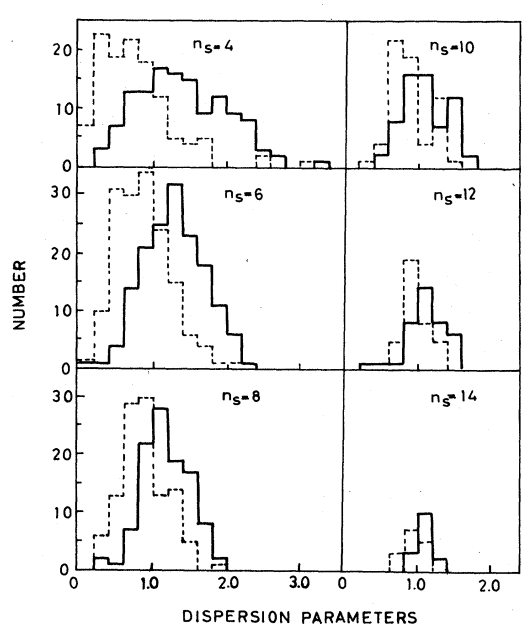

FIG. 1. The distribution of δ and δ^1 calculated from individual even n_s events. The solid lines represent δ and the dashed lines, the δ^1 distribution.

A strong prediction[2] of the multiperipheral cluster model is that w^1 should vary with charged-particle multiplicity (n_s) as $\propto n_s^{-1/2}$. In Fig. 3, we have shown the variation of w^1 with n_s. For comparison, the data at 303 and 40 GeV are also given. At all the energies, the trend of variation of w^1 with n_s is the same, indicating energy independence of the clusterization property. The solid curves indicate the fit $w^1 = an_s^{-1/2}$ to the data points. The curves seem to be good representations of data points and yield good values of χ^2, as shown in the figure. This suggests that the particles, especially at high multiplicities, might be emitted via cluster formation, under a multiperipheral scheme.

Having thus confirmed, through various dispersion parameters, that significant clusterization effects are present in the data, we now analyze the rapidity distribution to estimate the cluster parameters.

B. Cluster parameters

The rapidity distribution for the low-multiplicity ($n_s = 4$ to 6) and high-multiplicity ($n_s = 7$ to 15) events have been shown in Fig. 4. The two groups contain 385 and 416 events, respectively. Therefore, the low-multiplicity distribution has been multiplied by a factor of 1.08 in order to make the number of events the same in the two groups. It is observed that the bases of the two distributions have the same length which is consistent with the kinematical limit $\eta_{max} = 6.8$.

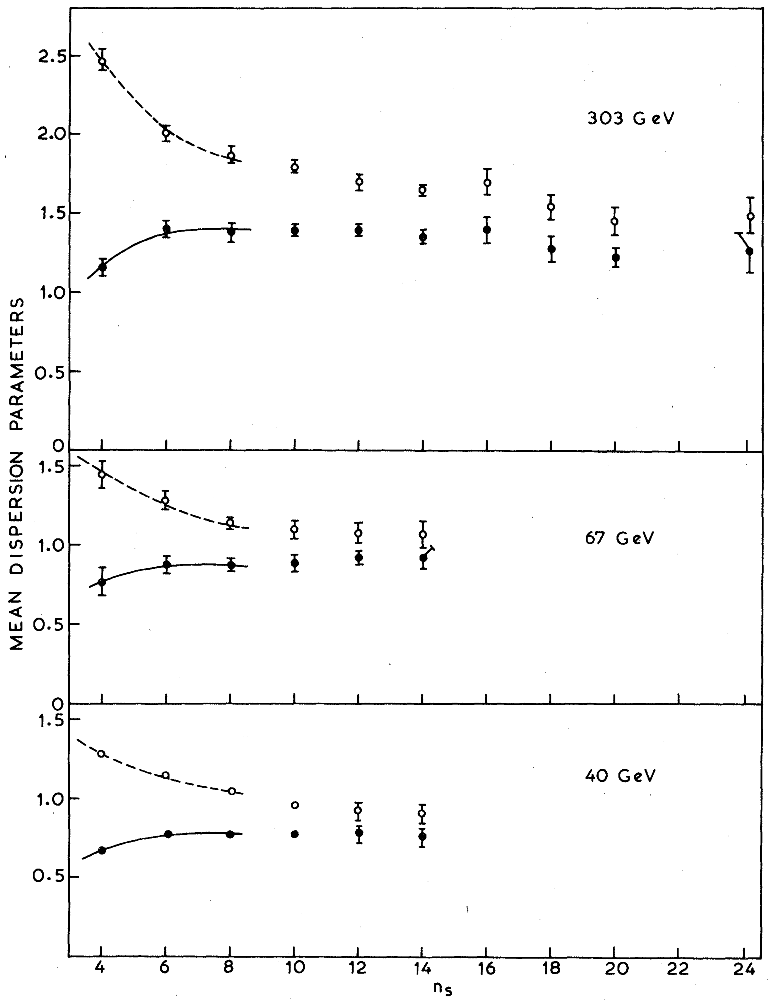

FIG. 2. The variation of $\bar{\delta}$ (shown as ○) and $\bar{\delta}^1$ (shown as ●) with charged-particle multiplicity. The points at 303 GeV are based on calculations from the projected angles. The curves are drawn to show the trend of variation.

The overlapping portions of the two distributions provide a natural separation of the rapidity distribution into three regions, namely, target fragmentation region having $0 \leq \eta \leq 1.0$, central region having $1.0 < \eta \leq 4.4$, and projectile fragmentation region having $4.4 < \eta \lesssim 6.8$. The characteristics of these regions are shown in Table II.

In the central region of rapidity, the mean

TABLE II. Characteristics of the target, projectile, and central region of rapidity.

		Target fragmentation region $0 \leq \eta \leq 1.0$		Projectile fragmentation region $4.4 < \eta \leq 6.8$		Central region $1.0 < \eta \leq 4.4$		
							Number of charged particles	
Multiplicity (n_s)	Number of events (a)	Number of charged particles (b)	Number of charged particles per event (b/a)	Number of charged particles (c)	Number of charged particles per event (c/a)	Width of rapidity distribution (d)	Total (q)	Per event per unit rapidity (q/da)
4 to 6	385	169	0.44	352	0.91	3.8	1441	0.99
7 to 15	416	211	0.51	355	0.85	2.6	3326	3.08

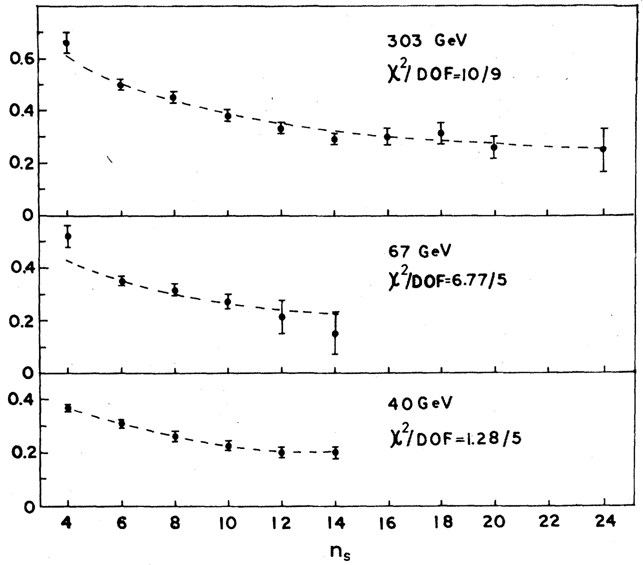

FIG. 3. The variation of w^1 with the charged-particle multiplicity. The curves are the best fits from $w^1 = a n_s^{-1/2}$. The values of a for 40, 67, and 303 GeV are 0.74, 0.86, and 1.22, respectively.

widths (which we define as the total width at half height) of the distributions for low and high multiplicities are found to be 3.8 and 2.6, respectively. Thus, the plateau length diminishes significantly as one goes from low-multiplicity to high-multiplicity events. Such a decrease in the plateau length has been observed at 200 GeV (Ref. 7) also. In the central region, the number of charged particles per event per unit rapidity interval are found to be 0.99 and 3.08 for the low- and high-multiplicity events, respectively. However, the number of fragmentation particles per event in the two multiplicity groups remains almost the same (Table II). Thus, the growth of multiplicity is primarily due to the creation of additional particles in the central region of rapidity. It is presumably due to the production of more clusters in the high-multiplicity events than those in low-multiplicity events.

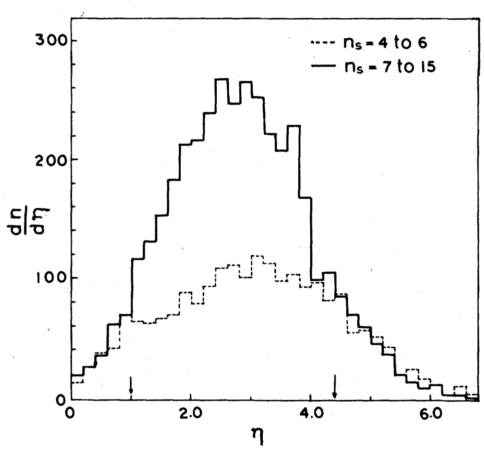

FIG. 4. The semi-inclusive distributions of rapidity for low-multiplicity (n_s=4 to 6) and high-multiplicity (n_s=7 to 15) events. The two distributions are normalized to the same number of events. The arrows divide the rapidity space into target fragmentation, central, and projectile fragmentation regions.

The overall cluster density (ρ) in the rapidity space can be found by the method of Adamovich *et al.*[8] in which one fits a distribution of the type

$$\frac{dn}{dr} \propto e^{-\rho r} \tag{8}$$

for large ($r \geq 0.8$) values of rapidity gaps $r = |y_{i+1} - y_i|$. Here ρ is the average number of clusters per unit rapidity interval. The value of ρ, obtained[9] by this method, comes out to be 0.5. Now, if ρ_1 and ρ_2 are the cluster densities for low- and high-multiplicity events, respectively, we may write

$$\frac{\rho_1 + 1.08\rho_2}{1 + 1.08} = \rho = 0.5\,, \tag{9}$$

where, as mentioned earlier, the total number of events in the two groups is in the ratio 1.08 : 1.

In view of our earlier observation that cluster parameters remain independent of multiplicity, we assume that the charged-particle multiplicity of each cluster is Z. Then,

$$\rho_1 Z = 0.99 \tag{10}$$

and

$$\rho_2 Z = 3.08 \tag{11}$$

as obtained earlier (see Table II). Here we assume that all the particles are decay products of clusters. Solution of Eqs. (9)–(11) yields $\rho_1 = 0.24$, $\rho_2 = 0.74$, and $Z = 4.14$. Thus, the probability of cluster production in a high-multiplicity ($n_s \geq 7$) event is about 3 times that in a low-multiplicity event. Using the charged-particle multiplicity of 4.1 as obtained above, the total number (including neutrals) of particles associated with a cluster is thus found to be $1.5 \times 4.1 = 6.2$. This is in agreement with the estimate 5–6 obtained by Ludlam *et al.*[10] in the 200–300 GeV range by an independent method known as fluctuation analysis.

It is interesting to note that the definition of a cluster as the group of particles for which $\delta^1 \leq 0.9$ is based on the isotropy of the cluster decay products in the cluster rest frame. In other words, it requires $\langle p_t \rangle \simeq \langle p_{\parallel} \rangle$ for the cluster decay products in the cluster rest frame. Berger *et al.*[1] have shown that this condition is satisfied for values of $1.5Z \gtrsim M/\langle p_t \rangle$, where M is the cluster mass and $1.5Z$ is the total number (including neutrals) of the cluster decay products. From this we get $M \lesssim 2.1$ GeV for $\langle p_t \rangle = 0.35$ GeV/c and $Z = 4.1$. This estimate of cluster mass from the present data is consistent with a number of earlier investigations.[11]

ACKNOWLEDGMENTS

We wish to thank Professor K. D. Tolstov of JINR, Dubna (U.S.S.R.) for sending us the 67-GeV/c collaboration data. N. S. Arya thanks the University Grants Commission (India) for granting him a teacher fellowship.

[1] E. L. Berger, G. C. Fox, and A. Krzywicki, Phys. Lett. 43B, 132 (1973).
[2] F. T. Dao *et al.*, Phys. Lett. 45B, 73 (1973).
[3] P. K. Sengupta *et al.*, Phys. Scr. 21, 17 (1980).
[4] Ts. Baatar *et al.*, Yad. Fiz. 26, 1022 (1977) [Sov. J. Nucl. Phys. 26, 541 (1977)].
[5] W. Burdett *et al.*, Vanderbilt-Brookhaven report, 1972 (unpublished).
[6] Alma Ata–Dubna–Cracow–Leningrad–Moscow–Tashkent–Ulan Bator collaboration, Joint Institute of Nuclear Research, Dubna, Data Book No. NPI-6504, 1972 (unpublished).
[7] P. L. Jain *et al.*, Lett. Nuovo Cimento 8, 921 (1973).
[8] M. I. Adamovich *et al.*, Nuovo Cimento 33A, 183 (1976).
[9] N. S. Arya *et al.*, Prog. Theor. Phys. 63, 939 (1980).
[10] T. Ludlam and R. Slansky, Phys. Lett. 48B, 449 (1974).
[11] M. M. Aggarwal *et al.*, Lett. Nuovo Cimento 22, 108 (1978), and references quoted therein.