Characteristics of rapidity-gap distribution at cosmic-ray energies ($\sim 10^{12}$ eV)

S. Roy, 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 10 August 1979)

A phenomenological study of the rapidity-gap distribution for cosmic-ray N-N interactions at energies $\gtrsim$ TeV has been reported. The observations indicate strong short-short correlations in rapidity gaps which support Snider's two-channel multiperipheral cluster model. The cluster size and cluster density at these energies have been estimated to be 6.5 and 1.0, respectively. It is found that with increasing energy, the cluster size practically remains constant but the number of clusters produced per collision rises slowly.

I. INTRODUCTION

It is now well known[1-6] that clusters are formed in the intermediate stage of the multiparticle production processes at high energies. Therefore, several attempts have been made to incorporate clustering effects within a general theoretical framework. In the framework of the general Chew-Pignotti multiperipheral model, two notable attempts have been made to incorporate the cluster phenomenon. One is by Quigg, Pirila, and Thomas[5] (QPT) and the other is by Snider.[6] QPT assume independent cluster emission for which some support is rendered by the two-particle correlation studies[7,8] at Fermilab and at CERN ISR. They suggest a simple Chew-Pignotti multiperipheral model with a single input trajectory $\alpha = 0.5$. On the other hand, Snider has suggested a two-channel Chew-Pignotti model with two different input Regge trajectories, one near $J = 0.5$ and the other near $J = -0.5$.

It is useful to find out whether the single-channel or the double-channel picture is in conformity with the experiment. The experimental distribution of rapidity-gap lengths between charged particles, adjacent in rapidity space, is a convenient tool to make distinction between these two models. In terms of such a distribution, Snider[9] has pointed out the following distinguishing features of these models.

(1) The rapidity-gap (r) distribution dn/dr in the central region of the rapidity space, as predicted by Snider's model, is of the form

$$dn/dr = Ae^{-x_1 r} + Be^{-x_2 r}\,, \tag{1}$$

where the constants A and B and the slopes x_1 and x_2 are fixed so as to give the correct total cross section, charged-particle density ($\simeq$2/rapidity units), asymptotic energy behavior of prong cross sections, and the two-particle correlation length. He thus obtains

$$dn/dr = 2.4e^{-3.1r} + 0.2e^{-0.9r}\,. \tag{2}$$

On the other hand, in the QPT model,[5] independent emission of clusters is assumed, and within a cluster the decay pions are taken as quite close to the central position of the cluster in rapidity space. Therefore, the rapidity-gap distribution at large gap sizes between the hadrons measures directly the gap distribution between the clusters. Hence,

$$dn/dr \approx e^{-\rho r}\,, \tag{3}$$

where ρ is the density of clusters in rapidity space. At small gap sizes, the expectation is that there would be an excess of events over those predicted by relation (3) due to the correlation effects.

(2) Regarding the rapidity-gap correlations, Snider's model implies[9] that next to a small gap ($r \leq 0.1$) is probably a small gap and next to a large gap ($0.8 \leq r \leq 1.0$) is probably a large gap, whereas the QPT model leads to the prediction that the gaps should tend to alternate, i.e., a small (large) gap should probably be followed by a large (small) gap. This is so because in this model each cluster has only two charged particles and these would generate a short gap.

(3) Another important parameter capable of distinguishing between the two models is the number of particles into which a cluster decays, viz., the cluster size. The QPT model,[5] in order to have the correct cross section and charged-particle density (~2/rapidity unit), assumes that an average of two charged particles are emitted per cluster. On the other hand, the high probability of short-short correlations predicted by the Snider's model requires that the average number of charged particles constituting a cluster should be greater than two. This is so because the most probable occurrence of two short gaps in succession needs three charged particles closely spaced in rapidity.

Recently we have reported studies on the above aspects by using the p-N data at 67 GeV (Ref. 10) and at 400 GeV (Ref. 11). In view of a rather clear distinction between the two models at 67 GeV as well as at 400 GeV, we thought that it would be worthwhile to extend our studies into the realm of cosmic-ray energies ($\gtrsim$TeV).

II. EXPERIMENTAL DETAILS

A total of 465 cosmic-ray N-emulsion interactions are available from ICEF data sheets,[12] and in addition 57 are available from the Chicago stack.[13] It is well known that the rapidity distributions for N-N and N-nucleus types of events are markedly different. In order to have a meaningful comparison of the experimental data with the theory, we have therefore selected only those events which can be classified as N-N type of interactions. The main criterion for this selection is that the number of heavy tracks (N_h) in an event should be zero. With this selection criterion we are left with a total of 40 N-N types of events for which the rapidity values have been compiled by Shivpuri *et al.*[14] Further we want to analyze the rapidity gaps for those particles which fall in the central region of the rapidity space. Therefore, out of n_s secondary tracks in an event, we ignore the first and the last (when ordered in rapidity) which may be due to the diffractive component. Hence n_s has to be ≥ 4. Only one event with $n_s = 2$ did not satisfy this criterion. The present study is finally based on a total of 557 shower tracks contributed by 39 events.

The energies of the primaries of these events have been estimated by various methods.[12,13] Among them Castagnoli's formula and the E_{ch} method seem to be most popular. These two methods give widely different values of energy. For the present work we do not require the energy of each primary particle as an essential parameter. However, on the basis of primary energies calculated by various methods we believe that a representative energy $\gtrsim$TeV would be quite appropriate for the sample of events used in the present work.

The rapidity y of a particle is defined as

$$y = \tfrac{1}{2}\ln[(E+P_{\parallel})/(E-P_{\parallel})]\,, \tag{4}$$

where E and $P_{\parallel}$ are, respectively, the total energy and the longitudinal momentum of a secondary particle. Obviously a determination of y requires not only the measurement of the angle of emission (θ) and the momentum (p) of a particle, but also its identity. However, at the high energies of the data under consideration, only the emission angles of the secondary particles could be accurately measured. Also, $\simeq 80\%$ of the secondary particles are believed to be pions; therefore, the inequality

$$p^2 \gg m_\pi^2 \tag{5}$$

is well satisfied for most of the secondary particles. Under this approximation, the definition (4) reduces to the form

$$y \approx \eta = -\ln\tan(\theta/2)\,, \tag{6}$$

where η is known as the pseudorapidity. We have calculated rapidity gaps using this approximation.

III. RESULTS AND DISCUSSION

The distribution of the rapidity gaps for the total sample has been shown in Fig. 1. The distribution, when fitted to an equation of the form (1) by a least-squares method, yields

$$dn/dr = 81.31e^{-6.5r} + 6.10e^{-1.0r}\,. \tag{7}$$

This equation on normalization to the Snider's theoretical curve [Eq. (2)] becomes

$$dn/dr = 4.39e^{-6.5r} + 0.33e^{-1.0r}\,. \tag{8}$$

The fits of Eqs. (7) and (8) give a χ^2 value of 28.6 for 36 degrees of freedom (DOF). On the other hand, when the data are fitted to a single exponential form, one gets

$$dn/dr = 83.57e^{-5.34r}\,, \tag{9}$$

with a χ^2 value of 56.7 for 38 DOF, which represents a very poor fit. Thus the data are in excellent agreement with a two-exponential rapidity-gap distribution as predicted by Snider's model.

It may however be noted that although the whole distribution cannot be represented by a single exponential term, it is evident from Fig. 1 that the distribution beyond $r \geq 0.8$ could be so represented. A fit due to a single-exponential form to

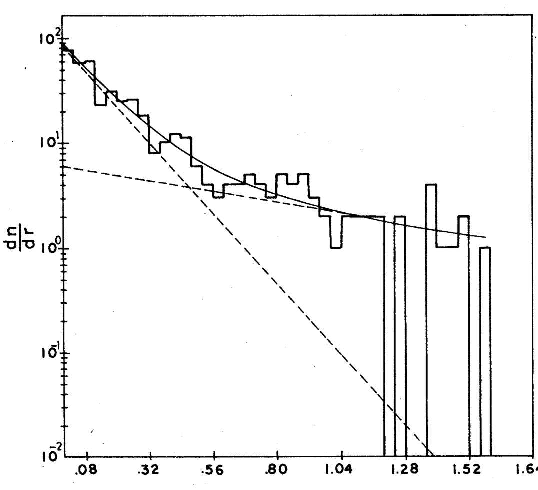

FIG. 1. Rapidity-gap (r) distribution at cosmic-ray energies. The solid curve is the best fit [Eq. (7)] to the data. The dashed lines show the contributions of the two exponential terms separately.

the data with $r \gtrsim 0.8$ yields

$$dn/dr \approx 6.1e^{-1.00r} . \tag{10}$$

Such behavior of dn/dr is expected from the QPT model as explained earlier. Thus we observe that the ordinary rapidity-gap distribution does not reveal much as to which of the two models explains the data.

The distinction between the two models can be effectively made if one studies another distribution, namely, the distribution of rapidity gaps next to a small gap.[9-11] This has been shown in Fig. 2. The distribution is peaked in the region $r = 0 - 0.12$ and then falls off sharply. For this distribution, it is interesting to study the ratio

$$R = N_1/N_2 , \tag{11}$$

where N_1 and N_2 are, respectively, the number of short gaps and large gaps in this distribution. The value of R for the present data is $\simeq 26$. This clearly shows that the probability of a short gap ($r \leq 0.1$), occurring after a short gap, is considerably higher than that of a large gap ($0.8 \leq r \leq 1.0$), occurring after a short gap. These observations, therefore, strongly favor the model due to Snider. At 67 (Ref. 10) and 400 (Ref. 11) GeV, the values of R are $\simeq 5$ and $\simeq 10$, respectively. This indicates that the dominance of short-short correlations appreciably increases with increasing energy.

A two exponential fit of the form (1) to the distribution of Fig. 2 yields

$$dn/dr = 43.86e^{-9.8r} + 3.23e^{-1.1r} , \tag{12}$$

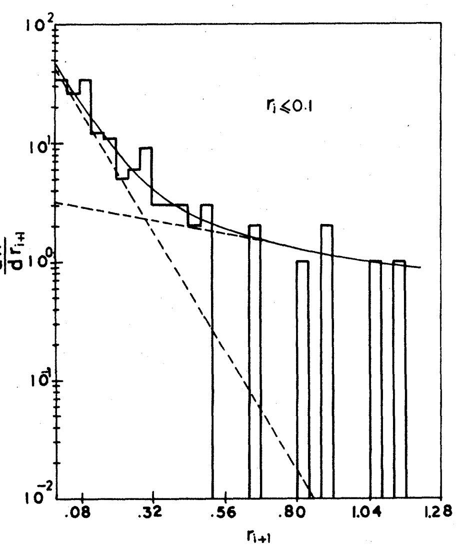

FIG. 2. The distribution of rapidity gaps (r_{i+1}) next to a short gap ($r_i \leq 0.1$). The solid curve is the best fit [Eq. (12)] to the data. The dashed lines show the contributions of the two exponential terms separately.

with a χ^2 of 12.1 for 26 DOF. A comparison of Eqs. (12) and (8) reveals that x_2 ($=\rho$) remains ~1, whereas the slope x_1 increases from 6.5 to 9.8. It emphasizes that the three-particle (or short-short) correlations are quite significant, and the average cluster size should be greater than two.

Thus one can conclude that the observed rapidity-gap distribution and the inferred characteristics of the three-particle correlations for the cosmic-ray data are in good agreement with the predictions of Snider's model. On the other hand, although the QPT model can very well describe the rapidity-gap distribution for large gaps and yields a simple method to estimate the cluster density, it yet fails to explain the observed features of the three-particle correlations. In view of the agreement of our data with Snider's model, we now investigate the various other features of this model.

According to Snider's model, one expects a dip in dn/dr around $r = 0.0$. As is evident from Fig. 1, no such dip is observed for the present data. The absence of a dip has also been noted at 67 (Ref. 10), 200 (Ref. 6), and 400 (Ref. 11) GeV. The fact that the occurrence of the dip has not been marred by the choice of the rapidity interval in Fig. 1 can be ascertained by splitting the first bin (0–0.04) into two bins, viz., (0–0.02) and (0.02–0.04). The numbers of gaps in these two bins are 42 and 34, respectively. This again indicates a rising trend of the distribution at small gap sizes. Therefore, following Snider,[6] it may be presumed that, in case of particle production in the central region of the rapidity, the effects of hard-core repulsion are not important. It may also mean, as Snider[6] states, that "complex-poles" concepts are not important in the central region of rapidity.

It is interesting to study the variation of the constants A, B, x_1, and x_2 (or ρ) occurring in Eq. (1) with energy. The values of these constants for p-N interactions at 67 (Ref. 10) and 400 (Ref. 11) GeV along with those for the present cosmic-ray data are shown in Table I. There appears to be a tendency of these constants to increase with energy. The increase of x_1 implies the increase of two-particle correlations in rapidity space, and the increase of x_2 (or ρ) indicates that the process of cluster formation gets stronger at higher energies.

It is worthwhile to understand, through an alternative approach, whether, with the increase in energy, the clusters grow heavier or their number increases. Adamovich *et al.*[15] have shown that the rapidity-gap distribution, in the limiting cases, can be usefully parametrized in the following way:

$$dn/dr \simeq e^{-\rho m r} \quad (\text{for small } r) , \tag{13}$$

and

TABLE I. The values of A, B, x_1, x_2 (or ρ), and m at different energies.

Energy (GeV)	A	B	x_1	x_2	m	Reference
67	2.40 ± 0.04	0.030 ± 0.001	2.60 ± 0.03	0.50 ± 0.02	5.2	10
400	2.98 ± 0.12	0.18 ± 0.01	3.90 ± 0.08	0.70 ± 0.06	5.6	11
$\gtrsim 1000$ (cosmic rays)	4.39 ± 0.20	0.33 ± 0.03	6.50 ± 0.20	1.00 ± 0.12	6.5	Present work

$$dn/dr \simeq e^{-\rho r} \quad \text{(for large } r\text{)}, \tag{14}$$

where m denotes the total number of particles (including the neutrals) constituting a cluster and ρ is the number of clusters produced per unit rapidity invertal. The values of these parameters for the present cosmic-ray data along with those for the 67-GeV (Ref. 10) and 400-GeV (Ref. 11) p-N interactions are shown in Table I. Ludlam and Slansky,[16] through a fluctuation analysis, have estimated $m \simeq 5-6$. This is in good agreement with the values of m (shown in Table I) for a wide energy range from 67 to $\lesssim 1000$ GeV. This shows that m has a very weak dependence on energy, as predicted by several authors.[17-19] On the other hand, ρ tends to grow logarithmically with energy. Thus it seems that the cluster size practically remains constant but the number of clusters produced per collision rises slowly with increasing energy.

ACKNOWLEDGMENT

S. Singh and S. Roy wish to express their gratitude to Dr. N. S. Pradhan, Principal, Kirori Mal College (University of Delhi) for constant help and encouragement.

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