Correlations among secondary particles in nucleon–light-nucleus interactions at cosmic-ray energies

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Evidence for the existence of strong two-particle correlations in nucleon-nucleus interactions at cosmic-ray energies ($\sim 10^{12}$ eV) is presented here. The results are compared with nucleon-nucleon interactions at the same energies. It is found that there is no essential difference in the characteristics of clusters in these two classes of interactions.

I. INTRODUCTION

The existence of correlations among the secondary particles has convincingly proved the production of clusters in high-energy interactions. A number of investigations[1] have been carried out to study the dynamics of cluster production and other basic features of the cluster model. The interactions studied so far have been of the nucleon-nucleon type. It would be interesting to investigate whether cluster production is evident in nucleon-nucleus interactions and also if the cluster characteristics are modified when the target consists of more than one nucleon. We present here a first investigation of the existence of correlations in nucleon–light-nucleus interactions at cosmic-ray energies (~10^{12} eV), and compare it with the cluster characteristics in nucleon-nucleon interactions at the same energies.

The production of clusters in nucleon–light-nucleus interactions at cosmic-ray energies (~10^{12} eV) is shown by means of two-particle rapidity-difference distributions. Positive short-range correlations are present in these interactions. The dependence of the strength of correlation on the primary energy and multiplicity of the events is also investigated here. It is found that the strength of correlation is independent of the primary energy but increases with an increase in multiplicity.

Nuclear emulsion offers two groups of nuclei, light (C, N, O) and heavy (Ag, Br), besides the H nuclei. The interactions with H nuclei are of the nucleon-nucleon type and their heavy-prong number[2] (n_h) is zero. Although it is difficult to isolate an event belonging to a particular nucleus, by following a selection criterion the interactions from the light and heavy groups of nuclei can be broadly identified. In order to distinguish between the interactions due to light and heavy nuclei in emulsion, Friedlander[3] proposed a criterion on the basis of multiplicity of heavy prongs in an event. In a plot of n_s vs n_h, he obtained a kink at $n_h = 4-7$, which he attributed to the transition between light and heavy nuclei. Events with $n_h \leq 4$ were attributed to light nuclei, those with $n_h > 7$ to heavy nuclei.

The experimental data used here are taken from the ICEF data sheet,[4] and the following criteria were adopted to select the events.

(1) The primary energy (E_p) of the interaction must be greater than 0.1 TeV.

(2) The number of low-energy particles (heavy tracks, n_h) should be 1–4. By following this criterion a majority of the interactions would belong to the nucleon–light-nucleus category.

The number of events satisfying the above criteria was found to be 112, yielding the number of secondary particles equal to 1986. The interactions considered here are semi-inclusive processes since the rapidities of only the charged secondary particles are determined. The value of the rapidity is given by

$$Y = \tfrac{1}{2} \ln\left(\frac{E + P_L}{E - P_L}\right), \tag{1}$$

where E and P_L denote the energy and longitudinal momentum of the secondary particles, respectively. At cosmic-ray energies it can be assumed that $P_L \gg P_T \gg m$, where P_T and m denote the transverse momentum and mass of the secondary particles, respectively.

Hence from Eq. (1) we get

$$Y = \ln\left(\frac{2}{\tan\theta}\right), \tag{2}$$

where θ is the laboratory angle of the secondary particle.

The value of the primary energy in an interaction was determined by using the following formula of

Castagnoli *et al.*:[5]

$$\log\gamma_c = \frac{1}{n_s}\langle \log\cot\theta\rangle\,, \tag{3}$$

where $\gamma_c = 1/(1-\beta_c^2)^{1/2}$, β_c is the velocity of the center of mass, and n_s is the multiplicity of the charged secondary particles in an event. The value of the primary energy was found from the relation

$$E_p = M_n(2\gamma_c^2 - 1)\,, \tag{4}$$

where M_n is the nucleon mass. The contribution of the persisting primary in an interaction was not considered in the determination of γ_c as it is not a created particle and this procedure leads to a better estimate of the primary energy.[6] The primary energy of the interactions ranges from 0.1 to 50 TeV.

II. RESULTS AND DISCUSSION

A. Rapidity-difference distributions for $E_p > 1$ TeV and $E_p < 1$ TeV

The existence of a sharp peak at small values of the rapidity-difference (r) in the distribution of rapidity-gap lengths between two adjacent particles imply the presence of two-particle correlations. Various investigators[1] have proposed a cluster model which describes the two-particle correlations and rapidity-difference distributions for the nondiffractive component of the hadronic cross section at high energies. In the present work the rapidity-difference was calculated for neighboring charged particles. We have considered the secondary particles in the central region and have neglected the two leading particles on each end of the rapidity space. Hence the contribution of a Pomeron at the ends of the rapidity distribution is eliminated. Thus an event with multiplicity n contributed to the distribution $n-3$ times. The rapidity-difference distribution thus obtained is for the central plateau of the rapidity distribution.

Figures 1(a) and 1(b) show the two-particle rapidity-difference distribution for primary energy greater than 1 TeV and less than 1 TeV, respectively. The narrowness of the two-particle distributions indicates strong, positive clustering of the secondary particles. The mean multiplicity and mean energy of the events for $E_p < 1$ TeV and $E_p > 1$ TeV are 14 and 0.4 TeV and 22 and 8.5 TeV, respectively. In Figs. 1(a) and 1(b) the numerical equations for the theoretical curves represented by solid lines are, respectively, given by

$$dn/dr = 4.9e^{-5.4r} + 0.12e^{-0.8r} \tag{5}$$

and

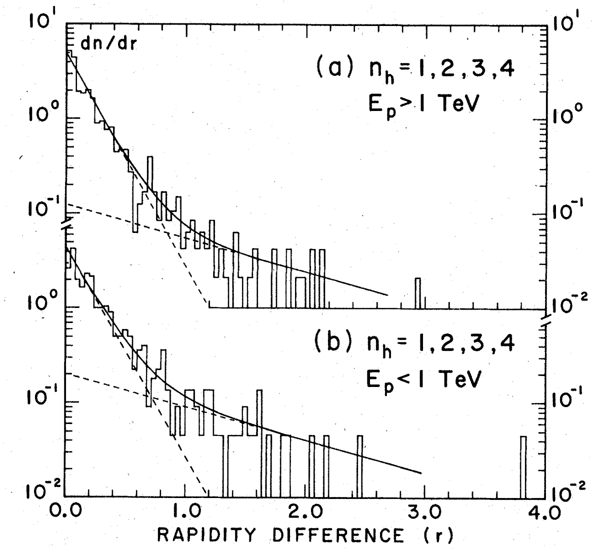

FIG. 1. Rapidity-difference (r) distribution for neighboring charged secondary particles for $n_h = 1, 2, 3,$ and 4 having primary energy (a) greater than 1 TeV and (b) less than 1 TeV, respectively. The solid curves in (a) and (b) show the respective contribution of Eqs. (5) and (6) in the text, and the dashed lines show the individual contribution of the two terms in the two equations.

$$dn/dr = 4.3e^{-5.1r} + 0.2e^{-0.8r}. \tag{6}$$

The dashed lines in Figs. 1(a) and 1(b) show the contributions of the two individual terms in Eqs. (5) and (6) and are also a measure of the slopes in each case. These relations compare well with the following relations which have been given earlier[7] for nucleon-nucleon interactions at the same energies for $E_p > 1$ TeV and $E_p < 1$ TeV, respectively:

$$dn/dr = 4.2e^{-5.1r} + 0.3e^{-1.0r} \tag{7}$$

and

$$dn/dr = 4.0e^{-4.8r} + 0.3e^{-0.7r}. \tag{8}$$

It can be noted that all these equations follow the form

$$dn/dr = Ae^{-Br} + Ce^{-Dr}. \tag{9}$$

The similar form and magnitude of the exponential relations (5) and (6) show that the two-particle correlations in the central region are energy independent. This supports the independent emission of clusters in these interactions. We have proposed earlier[7] that the value of the slope B in the first exponential term is a measure of the strength of the correlation among the secondary particles. We find that the values of the slope B in Eqs. (5) and (6) are 5.4 and 5.1 for $E_p > 1$ TeV and $E_p < 1$ TeV, respectively, and are nearly the same as in the case of nucleon-nucleon interactions. In the latter interactions the values of B are 5.1 and 4.8 for $E_p > 1$ TeV and $E_p < 1$ TeV, respectively. This shows clearly that the strength of correlation is independent of the primary energy and its value is nearly the same in both types of interactions.

B. Rapidity-difference distributions for $n_s \geq 14$ and $n_s \leq 9$

The variation of the rapidity-difference distribution of the secondary charged particles for the two ranges of multiplicity, *viz*, (a) $n_s \geq 14$ and (b) $n_s \leq 9$, is investigated. Figures 2(a) and 2(b) show the rapidity-difference distribution for events having $n_s \geq 14$ and $n_s \leq 9$, respectively. The theoretical curves for the distributions represent a double exponential distribution of the form given by Eq. (9). The numerical equations for the theoretical curves represented by solid lines in Fig. 2(a) for $n_s \geq 14$ and in Fig. 2(b) for $n_s \leq 9$ are, respectively,

$$dn/dr = 5.8e^{-6.3r} + 0.12e^{-0.8r} \tag{10}$$

and

$$dn/dr = 2.3e^{-3.1r} + 0.3e^{-0.8r}. \tag{11}$$

These equations compare well with the following relations which have been given earlier[8] for nucleon-nucleon collisions at the same energies for $n_s \geq 14$ and $n_s \leq 9$, respectively:

$$dn/dr = 5.5e^{-6.3r} + 0.2e^{-0.8r} \tag{12}$$

and

$$dn/dr = 2.1e^{-2.8r} + 0.3e^{-0.7r}. \tag{13}$$

The values of the slope B in the first exponential terms are 6.3 and 3.1 for $n_s \geq 14$ and $n_s \leq 9$, respectively. We thus find a stronger correlation in high-multiplicity events than in the low-multiplicity events. These values of B also compare well with the values of B in the case of nucleon-nucleon interactions, which are 6.3 for $n_s \geq 14$ and 2.8 for $n_s \leq 9$, respectively. The explanation for the dependence of the strength of correlation on multiplicity has been discussed in detail earlier.[8] The constant value of the slope D ($D = 0.8$) in the second exponential term for low- and high-multiplicity events signifies the independent emission of particles contributing in this region of the rapidity-difference distribution.

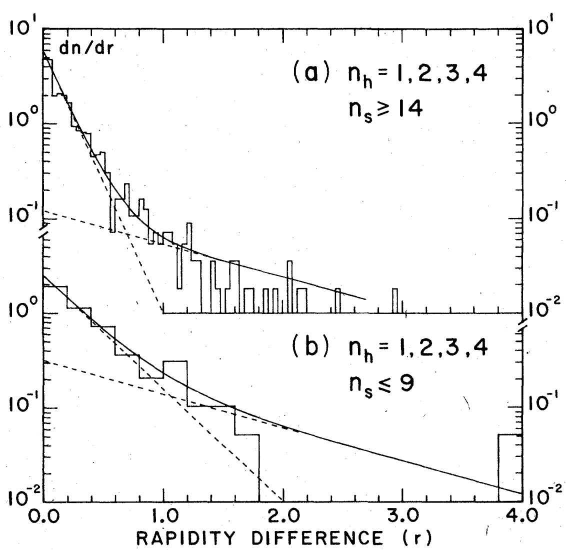

FIG. 2. Rapidity-difference (r) distribution for neighboring charged secondary particles for $n_h = 1$, 2, 3, and 4 having multiplicity (a) $n_s \geq 14$ and (b) $n_s \leq 9$, respectively. The solid curves in (a) and (b) show the respective contributions of Eqs. (10) and (11) in the text, and the dashed lines show the individual contribution of the two terms in the two equations.

III. CONCLUSIONS

The existence of strong short-range correlations is clearly observed in nucleon–light-nucleus interactions. These correlations can be understood on the basis of the cluster production in such interactions. It is also found that the characteristics of the clusters in nucleon–light-nucleus events are the same as in the case of nucleon-nucleon interactions. This can be understood from the behavior of the parameter ν, which denotes the number of collisions suffered by the primary in the nucleus. Considering multiple collisions to take place in a nucleus, the c.m.-system. Lorentz factor γ_c is a decreasing function of the number ν of target nucleons,[3]

$$\gamma_c = (\gamma_0 + \nu)(1 + \nu^2 + 2\gamma_0\nu)^{-1/2},$$

where γ_0 is the Lorentz factor of the primary nucleon in the laboratory system. The value of ν is slightly greater than 1 in the case of light nuclei in emulsion. Hence the interaction in such cases is essentially of a nucleon-nucleon type. The value for the number of collisions inside a light nucleus obtained by Barashenkov *et al.*[9] is 1.4 at 9 GeV and that obtained by A. Barbaro-Galtieri *et al.*[10] at 27 GeV is 1.1. As the primary energy increases, the number of collisions decreases further. Anderson and Otterlund[11] have argued that the value of n_h can be taken as a monitor of the value of ν. Events having low values of n_h can be taken to be effectively nucleon-nucleon collisions. Hence the cluster characteristics are similar in N-N and N–light-nucleus interactions.

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[2]Following the usual nomenclature, tracks having an ionization >1.4 times the minimum are termed heavy tracks (n_h) and those having an ionization $\leqslant$1.4 times the minimum are called shower tracks (n_s). The former are due to knock-on nucleons and the evaporation of nuclei, and the latter are due to elementary nucleon-nucleon collisions.

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