Direct Evidence for Independent Emission of Clusters

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ABSTRACT

In the distribution of rapidity gaps between charged particles produced at FermiLab energies, we find direct evidence for the independent production of clusters with density approximately one per unit of rapidity. This model-independent cluster density measurement and the observed charged-particle density imply that the mean number of charged particles per cluster is about two. Implications of these numbers and techniques for refining them are discussed.

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Although considerable circumstantial evidence suggests that the short-range correlations among produced particles observed at FermiLab and the CERN ISR may be ascribed to the independent emission of clusters,[1] no direct confirmation of this picture has previously been presented. Moreover, because the observable effects cited as evidence for clustering are insensitive to the detailed properties of clusters, the characteristics of clusters -- other than range -- have been established only deviously, with heavy reliance on specific models.[2] Recently it was shown[3] that the distribution $P(r)$ of rapidity gap lengths between charged particles adjacent in rapidity contains the same sort of information as the two-particle correlation function in (it was hoped) more accessible form. In this Letter we establish the usefulness of the rapidity gap distribution by proving that (i) the form $P(r) \propto \exp(-\rho r)$ assumed by the rapidity gap distribution for large gap lengths is a direct consequence of independent cluster emission; (ii) the exponential slope ρ is the density in rapidity of independently-emitted clusters which decay into at least one charged particle; (iii) a deviation from exponential behavior at small separations, in the form of upward curvature, establishes that clusters decay in the mean into more than one charged particle. In addition to these new qualitative results, we shall present and interpret numerical information based on 205 GeV/c pp collisions.

In the independent cluster emission model it is assumed that

clusters of hadrons are produced independently (therefore according to

a Poisson multiplicity distribution) in the available rapidity interval.

Each cluster decays independently of its fellows, the probability g_M

for decay into M particles being the same for all clusters. The M decay

products of a cluster emitted at rapidity $\hat{y}$ are distributed in an uncorrelated

manner according to

$$D(\hat{y} - y_1)D(\hat{y} - y_2) \ldots D(\hat{y} - y_M),$$

where $D(y) \approx (2\pi\delta^2)^{-\frac{1}{2}} \exp(-y^2/2\delta^2)$ and the assumption of isotropic

decay implies $\delta \approx 0.85$.

The distribution of gaps between independently-emitted objects

is[4]

$$P(r) = \rho \exp(-\rho r) \qquad (1)$$

where ρ is the density in rapidity of the emitted objects and r is the

separation between adjacent objects. The experimental distribution

of gaps between charged particles is shown in Fig. 1. It is not

described by a single exponential, which is unsurprising because the

charged-particle multiplicity distribution is known to be broader than

Poissonian ($f_2 > 0$). We now argue that if clusters are produced,

Eq. (1) is appropriate for the (unobservable) gaps between

clusters but is inappropriate for gaps between particles

unless the particles are so widely separated the particles must be

products of different clusters. If clusters are localized, short-range

objects, the last-mentioned situation is attainable and we should observe

the onset of the exponential behavior of (1) when the gap length exceeds

the typical range of a cluster ($\sim$ 1 unit of rapidity). An exponential

dependence can indeed be ascribed to the large-gap data; the slope implies

a cluster density $\rho \approx 1$.

To proceed further, we observe that if the cluster density is

approximately 1 and the directly-observed[6] charged pion density $\rho_\pi \approx 2$,

the mean number of charged pions per cluster , $<M>$, must be roughly

2. If clusters were neutral, we would expect (1) to hold down to small

separations for gaps between negative particles, since the probability

for two negatives to emerge from a single cluster would be exceedingly

small. The remaining data in Fig. 1 show this to be the case: the slope

for gaps between negatives coincides with the large-gap slope for the

all-charged-particles distribution.

To this point we have confirmed directly, on a qualitative level,

that clusters of limited extent in rapidity are produced independently.

This conclusion does not rely upon any dynamical assumption concerning

the underlying mechanism for cluster production, nor do we require any

assumption about the intracluster multiplicity distribution g_M to obtain

the result $<M> \simeq 2$. To manifest the consistency of our interpretation,

we next explain the gap length distribution over its full observed range.

Beyond providing an important independent test of our ideas, this

exercise brings to light a means of determining more sensitively the

parameters of a cluster model.

Once the cluster density and the intracluster multiplicity distribution are specified, the rapidity gap distribution is completely determined. Indeed, it will turn out that in first approximation the inclusive rapidity gap distribution is sensitive only to $<M>$, and not to higher moments of the intracluster multiplicity distribution.

Each secondary emerging from a cluster at $\hat{y}$ has the independent probability

$$q_{12}(\hat{y}) = \int_{y_1}^{y_2} dy\, D(y-\hat{y}) \tag{2}$$

to occupy the interval (y_1, y_2). Therefore, the probability that an M-particle cluster at $\hat{y}$ deposits no particles in the interval of interest is

$$G_M(y_1, y_2; \hat{y}) = \left[1 - q_{12}(\hat{y})\right]^M. \tag{3}$$

If several clusters are produced, we combine these probabilities, weighting by the probability $\exp(-<N>)<N>^N/N!$ that N clusters be made and by the probability g_M that a cluster emits M observed particles. Thus, the probability that a single cluster is produced anywhere in the allowed rapidity interval $-Y/2, Y/2$ and deposits no particles in (y_1, y_2) is

$$\exp(-<N>) \sum_M g_M \frac{<N>^1}{1!} \frac{1}{Y} \int_{-Y/2}^{Y/2} d\hat{y} \left[1-q_{12}(\hat{y})\right]^M, \tag{4}$$

where we have weighted equally all cluster positions. At sufficiently

large energies, this approximation introduces only a small error. Next,

the probability that two independent clusters deposit no particles in

(y_1, y_2) is

$$\exp(-<N>) \sum_{M_1, M_2} g_{M_1} g_{M_2} \frac{<N>^2}{2!} \frac{1}{Y^2} \int_{-Y/2}^{Y/2} d\hat{y} \left[1-q_{12}(\hat{y_1})\right]^{M_1} \int_{-Y/2}^{Y/2} d\hat{y}_2 \left[1-q_{12}(\hat{y}_2)\right]^{M_2}. \quad (5)$$

Summing over all cluster multiplicities, we obtain for the probability

that no particles are produced in (y_1, y_2)

$$G(y_1, y_2; Z) = \exp\left\{\frac{<N>}{Y} \sum_{M=0}^{\infty} g_M Z^M \int_{-Y/2}^{Y/2} d\hat{y} \left\{\left[1-q_{12}(\hat{y})\right]^M - 1\right\}\right\}, \quad (6)$$

where we have weighted each coefficient g_M by Z^M to keep track of the

number of produced particles. If the right-hand side of (6) is expanded

in a power series in Z, the coefficient of Z^n is the probability that in

an n-particle event, no particles appear in (y_1, y_2). The inclusive average

is given by $Z = 1$.

Hereafter we identify the cluster density as

$$\rho = <N>/Y \quad (7)$$

and work in the high-energy limit $(Y \to \infty)$, in which G becomes a function

only of $r \equiv y_2 - y_1$ and Z. The frequency distribution for at least one

particle to occur at y_1 and no particles to occur in (y_1, y_2) is[7]

$(\partial/\partial y_1) G(y_1, y_2; Z)$. The frequency with which at least one particle occurs

at the other end of the gap $y_2 = y_1 + r$, independent of y_1, is precisely

the rapidity gap distribution. It is given by

$$P(r;Z) = \frac{-1}{\rho<M>} \frac{\partial}{\partial y_2} \frac{\partial}{\partial y_1} G(y_1, y_2; Z)$$

$$= \frac{1}{\rho<M>} \frac{\partial^2}{\partial r^2} G(r;Z) , \qquad (8)$$

which depends only on the gap length and Z.

To compare this result with the data, we compute $P(r; Z = 1)$ using

a Poisson intracluster multiplicity distribution with $<M> = 2$. The

results are shown in Fig. 1 to agree well with the data over the entire

measured range. We have verified that other choices for g_M, constrained

to give $<M> \simeq 2$, are equally satisfactory.[8] Distinctions among various

models can be drawn by confronting predictions with data for $Z \neq 1$.

The relevant parameter for arbitrary Z is $<M>_Z$. Given this average

for all values of Z we could in principle extract the distribution g_M.

Our present analysis establishes for the first time that multi-

hadron clusters are emitted independently, and demonstrates yet again the

existence of short-range correlations. Knowledge of the cluster density

is here extracted directly from the data without an intervening model.

All previous estimates of this number, and of the related mean number of

charged particles per cluster <M>, have been obtained less reliably,

since specific model or theoretical assumptions were needed as additional

input. Nevertheless, most of these estimates are in qualitative agreement

with our measurement.

For example, the one-channel Chew-Pignotti multiperipheral model, in which produced particles are strongly ordered in rapidity, relates the density of produced objects to the input trajectory α_0 by $\rho = 2 - 2\alpha_0$. Thus the usual meson exchanges with $\alpha_0 = 1/2$ give unit density, consistent with our measurement.[9]

Two-particle rapidity correlations are consistent with the shape predicted by the isotropic cluster decay picture. Assuming independent cluster emission to be the source of short-range correlations, and under specific assumptions about the diffractive component of multiple production, one can estimate $<M(M-1)>/<M>$. If in addition a specific form is assumed for g_M, $<M>$ can be extracted.[10] The uncertainties introduced by the indirectness of these estimates are indicated by the fact that estimates vary from[10] $<M> \simeq 2$ to[11] $<M> \simeq 4$.

Another estimate, based upon a direct measurement of charge mobility but a specific "ω" cluster model for charge transfer fluctuations leads to $\rho \simeq 1$.[12] The consistency of these many estimates, together with the direct evidence we have presented for independent cluster emission, argues convincingly in favor of the cluster description.

Our measurements of ρ and $<M>$ carry a number of additional important implications. That ρ is clearly not less than $\frac{1}{2}$ nor more than 2 will severely constrain overlap function calculations which have in the past been based upon widely varying guesses for ρ.[13] The small value

we find for <M> indicates that the properties of clusters closely resemble those of the prominent meson resonances. In our opinion, this adds to the intuitive appeal of the cluster picture.

We intend to investigate several additional properties of clusters with the techniques outlined here. Among the most important questions concerns the energy-dependence of the cluster parameters. By extracting g_M from the semi-inclusive data at various energies, we can test the attractive assumption that the intracluster multiplicity distribution is only weakly energy dependent. A related issue is whether, at a given energy, high-multiplicity events are produced by more clusters or bigger clusters. Finally, it is possible to study gap distributions for the exchange across the gap of a definite charge. These are sensitive to the net charge carried by clusters, and can test whether the cluster production mechanism is a multiperipheral exchange.

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FOOTNOTES AND REFERENCES

[1] A. W. Chao and C. Quigg, Phys. Rev. D9, 2016 (1974); S. Pokorski and L. Van Hove, Acta. Phys. Polon B5, 229 (1974).

[2] The extraction of information from two particle (semi-) inclusive correlation functions is reviewed by G. H. Thomas, ANL/HEP 7442 and Proc. XVII ICHEP, London.

[3] P. Pirilä and G. H. Thomas, ANL/ HEP 7448.

[4] If a derivation is required, it may be extracted from the general argument below.

[5] ANL/ FermiLab/ Stony Brook Collaboration, to be published.

[6] J. Whitmore, Phys. Reports 10C, 273 (1974).

[7] This is so because G is the cumulative distribution corresponding to the frequency function defined here. See, e.g., W. T. Eadie, D. Drijard, F. E. James, M. Roos, and B. Sadoulet, Statistical Methods in Experimental Physics (North-Holland, Amsterdam, 1972), p. 16.

[8] We have checked specifically a Kronecker delta distribution and the isoscalar $\rho\rho$ model. Each of these models also fits adequately the distribution of gaps between negative particles.

[9] A fit to the charged-particle rapidity gap distribution in a two-channel Chew-Pignotti model was presented by D. R. Snider, U. of Wisconsin-- Milwaukee preprint (unpublished). The parameters of the second channel do not have any direct physical interpretation.

[10] For primary references, see Refs. 1 and 2, and E. L. Berger, CERN preprint TH. 1800 (unpublished).

[11] R. Slansky, Phys. Reports 11C, 99 (1974).

[12] C. Quigg, to be published.

[13] Chan Hong-Mo and J. E. Paton, Phys. Lett. $\underline{46B}$, 228 (1973); C. Hamer and R. F. Peierls, Phys. Rev. $\underline{D8}$, 1358 (1973); A. Krzywicki and D. Weingarten, Phys. Lett. $\underline{50B}$, 265 (1974).

FIGURE CAPTION

Fig. 1   Distribution of rapidity gaps between produced particles in 205 GeV/c pp collisions (from Ref. 5). End gaps have been excluded from the data to minimize distortions due to diffractive events and kinematical constraints. The curves, which are predictions of a simple cluster model, are explained in the text.