Charge and Multiplicity Fluctuations in 205-GeV/*c* *pp* Interactions

T. Kafka, R. Engelmann, and M. Pratap
State University of New York at Stony Brook, Stony Brook, New York 11790*

and

Y. Cho, T. H. Fields, L. G. Hyman, and R. Singer
Argonne National Laboratory,† Argonne, Illinois 60439

and

L. Voyvodic, R. Walker, and J. Whitmore
Fermi National Accelerator Laboratory,‡ Batavia, Illinois 60510

(Received 18 November 1974)

Results on charge and multiplicity fluctuations in 205-GeV/*c* *pp* interactions are presented. The data are shown to be consistent with a simple picture of independent emission of low-multiplicity clusters, rather than of single pions, for the major part of the inelastic *pp* cross section.

In this Letter we present results on multiplicity and charge-transfer distributions using an inclusive sample of ~3500 inelastic 205-GeV/*c* proton-proton interactions obtained from an exposure of the Fermi National Accelerator Laboratory (FNAL) 30-in. hydrogen bubble chamber.[1] Earlier discussions of multiplicity distributions in the forward and backward center-of-mass (c.m.) hemispheres in the energy range 100–1500 GeV/*c* have been reported.[2,3] Data on the charge transfer across the c.m. hemisphere boundary have been presented in Ref. 3.

The kinematic variable used for the separation into the forward and backward hemispheres is the c.m. rapidity y. The mass assignments to each outgoing track for the calculation of y have been discussed in detail elsewhere.[4] That our hemisphere separation is reliable (on the average) is demonstrated by considering the average value of the charge transfer u across the c.m. hemisphere boundary,

$$u \equiv \tfrac{1}{2}(Q_f - Q_b)_{\text{final}} - \tfrac{1}{2}(Q_f - Q_b)_{\text{initial}} ,$$

where Q_b (Q_f) is the total charge in the backward (forward) hemisphere. For pp interactions the average charge transfer should be zero. From our data we find $\langle\langle u \rangle\rangle = 0.015 \pm 0.017$. One bracket denotes an average over data within a given multiplicity, while the second bracket denotes an average over all multiplicities.

Asymmetry studies of multiplicity cross sections[5] within a single c.m. hemisphere are expected to reveal whether a diffractive (fragmentation) or independent-emission (multiperipheral) mechanism dominates multiparticle production. Figure 1 shows, for different charged multiplicities n ($4 \leq n \leq 18$), the cross section for producing f particles in the forward hemisphere ($b = n - f$ particles in the backward hemisphere). The distributions have been folded and averaged about $f = b = n/2$. For $n \geq 6$ the distributions are symmetric with a maximum at $f = b = n/2$, i.e., events are most likely to have equal numbers of particles in each hemisphere, as expected in an independent-emission picture. Diffractively pro-

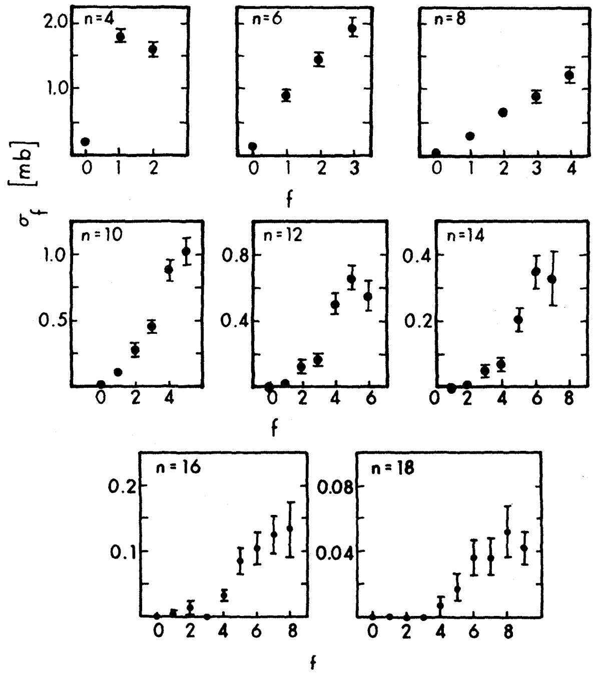

FIG. 1. Cross section for producing f particles in one c.m. hemisphere for different topologies n.

duced events are expected to be asymmetric with a minimum at $n/2$.[5] Such a contribution from configurations $f(b)=1$, $b(f)=3$ is seen in the data for $n=4$.[6] Results from 102-GeV/c pp interactions, published for $n \leqslant 8$, show a similar behavior.[3]

In an independent-emission picture one expects the mean squared charge transfer fluctuation across a boundary at any fixed y to be proportional to the charged-particle density $dn/dy=(1/\sigma)\,d\sigma/dy$[7,8]:

$$D^2(y)=\langle\langle u^2(y)\rangle\rangle-\langle\langle u(y)\rangle\rangle^2 \propto dn/dy. \qquad (1)$$

In Fig. 2(a) we compare the shape of $D^2(y)$ with a curve which represents dn/dy for charged particles with leading protons excluded.[9] Relation (1) is satisfied by our data. Similar results have been obtained at lower energies.[7,10] We find relation (1) to hold for semi-inclusive distributions as well, i.e., $D_n^{\,2}(y) \propto (\sigma_n)^{-1}\,d\sigma_n/dy$ for $n \geqslant 6$.

Asymptotically, diffractive models[11] predict that $\langle\langle u^2\rangle\rangle = D^2(0) \propto \sqrt{s}$, while an independent-emission calculation gives $\langle\langle u^2\rangle\rangle=\text{const}$.[2] Our value, for all charged particles, $\langle\langle u^2\rangle\rangle = 0.99 \pm 0.03$, at 205 GeV/$c$, is not significantly different from the measured value of $\langle\langle u^2\rangle\rangle = 0.90 \pm 0.04$ for 102-GeV/c pp interactions.[3] The variation of $\langle\langle u^2\rangle\rangle$ with s thus appears to be slower than $\sqrt{s}$.

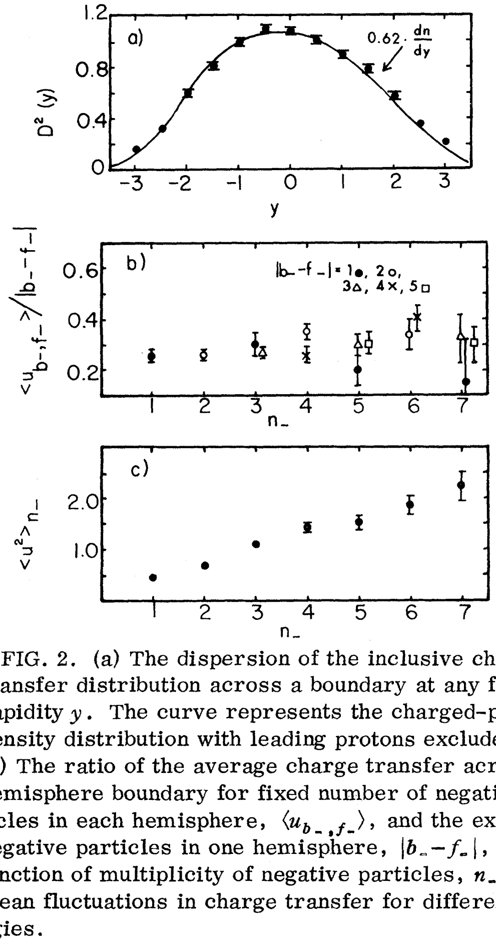

FIG. 2. (a) The dispersion of the inclusive charge transfer distribution across a boundary at any fixed rapidity y. The curve represents the charged-particle density distribution with leading protons excluded. (b) The ratio of the average charge transfer across the hemisphere boundary for fixed number of negative particles in each hemisphere, $\langle u_{b_-,f_-}\rangle$, and the excess of negative particles in one hemisphere, $|b_- - f_-|$, as a function of multiplicity of negative particles, n_-. (c) The mean fluctuations in charge transfer for different topologies.

The above results support the picture that in high-energy multiparticle production "something" is independently emitted. Independent emission of single pions, however, is not consistent with some known experimental results. For example, there is a positive correlation between neutral- and charged-pion emission in high-energy pp collisions.[13] An analysis of the event-to-event fluctuations in longitudinal phase space[14] and recent studies of the two-particle rapidity[15] and azimuthal[16] correlations suggest that the independent emission of low-multiplicity clusters can account for multiparticle production. Similarly, clustering effects are indicated by the observed magnitude of the mean charged-particle multiplicity[17] and the second moment of the multiplicity distribution, f_2. It is therefore of interest to compare the present data with a cluster picture in which neutral clusters are emitted.

In the further analysis of our data we use a simple asymptotic cluster model (because of the leading-particle effect the clusters are assumed not to participate in energy-momentum conservation) which is discussed in Refs. 12 and 8: Neutral clusters are independently emitted along the rapidity axis and decay as "ω" $\rightarrow \pi^+\pi^-\pi^0$ by placing one pion at the position y of the "ω" and the other two pions at rapidities $y+\Delta$ and $y-\Delta$, respectively. The parameter Δ is related to the cluster mass. Clusters in the interval $(y_0-\Delta, y_0+\Delta)$ deposit charged particles both to the left and to the right of y_0 with a probability $2\Delta/Y$. Here Y is the effective width of the rapidity distribution which we choose such that $(dn/dy)_{y=0}\cdot Y=\langle n_{\pi^\pm}\rangle$ and obtain $Y \simeq 4$. Both charge transfer and its fluctuation increase with increasing cluster mass. In particular,[8]

$$D^2(y)=\tfrac{2}{3}\Delta\, dn/dy.$$

From the scale factor in Fig. 2(a) we estimate $\Delta \simeq 0.9$.[18] Note that our value of $D^2(0)$ is inconsistent with the prediction for independent emission of single pions, $D^2(0)=\langle n_-\rangle=2.8$ at 205 GeV/c.

Figure 2(b) shows the average charge transfer for fixed number of negative particles in one hemisphere as a function of n_-. The values for different $|b_- - f_-|$ are approximately equal and independent of n_- as expected for independent emission.[12] The amount of charge transfer for "ω" clusters is[12]

$$\langle u_{b_-,f_-}\rangle/|b_- - f_-| = \tfrac{4}{3}\Delta/Y.$$

The expected value for independent emission of single pions is 0.5,[12] which is inconsistent with our data. Using an average value of $\langle u_{b_-,f_-}\rangle/|b_- - f_-| \simeq 0.3$, we find $\Delta \simeq 0.9$. In Fig. 2(c) the dependence of the charge-transfer fluctuation on topology is shown. The observed approximate linear rise is expected if independent emission is the production mechanism. From the "ω" cluster prediction,[12]

$$\langle u^2\rangle_{n_-} = \tfrac{4}{3}(\Delta/Y)n_-,$$

we get $\Delta \simeq 0.8$. The expected slope of 1 for independent emission of single pions is again inconsistent with the data.

In Fig. 3(a) we show the average multiplicity $\langle f\rangle$ in the forward hemisphere as a function of the number of particles in the backward hemisphere b (full circles). We believe that the minima at $b = 1$, 3 are partly due to the 1-1 configuration (1-3 and 3-1 configurations) of the diffractive two- (four-) prong events[6] and partly due to an odd-even effect caused by charge conservation which is more pronounced for lower multiplicities. For $b \geq 4$ there is a positive correlation between $\langle f\rangle$ and b. Emission of clusters provides a mechanism for such a correlation which increases with growing cluster mass.[8] Introduction of a suitable rapidity gap around $y = 0$ should eliminate this mechanism. This is achieved in our data for gap sizes greater than about $\frac{3}{2}$ (open circles) which roughly equals the value for 2Δ as derived from the charge-transfer data. The multiplicity fluctuations $\langle (f-b)^2\rangle$, given in Fig. 3(b) as a function of the number of negative particles n_-, is approximately proportional to n_-, as expected in independent emission. The fluctuation decreases with increasing cluster mass and the asymptotic prediction for the "ω" cluster is[8]

$$\langle (f-b)^2\rangle/n_- = 4(1 - \tfrac{4}{3}\Delta/Y).$$

From the measured fluctuation at average values of n_- (dashed line) we estimate $\Delta \simeq 0.6$. Note that the single-pion emission prediction[8]

$$\langle (f-b)^2\rangle/n_- = 2$$

is inconsistent with the data. The solid (Monte Carlo) curve[19] for single-pion emission agrees with the value 2 at average multiplicities and deviates from the asymptotic prediction because of charge and energy-momentum conservation.

Note that diffractive production would not give a correlation between f and b, and the asymmetric events would show a considerably larger forward-backward multiplicity fluctuation than shown in Fig. 3(b).

We conclude that our measurements of multiplicity cross sections in different hemispheres and charge-transfer cross sections in 205-GeV/c pp interactions are consistent with independent emission of low-mass clusters and inconsistent with single-pion emission. The clusters can be characterized, within the framework of the independent-cluster-emission model of Ref. 12, by a rapidity spread Δ of their decay products of $\frac{1}{2}$ to 1 unit in rapidity.

We are thankful to E. L. Berger, P. Grannis, G. Thomas, and C. N. Yang for interesting conversations. We are particularly indebted to C. Quigg for helpful suggestions and discussions about cluster models.

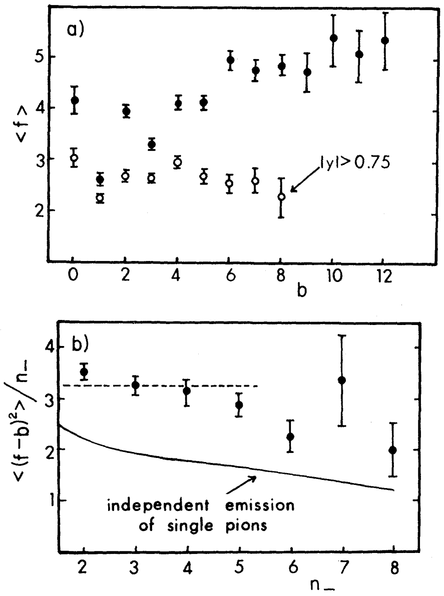

FIG. 3. (a) Average multiplicity $\langle f\rangle$ in the forward hemisphere as a function of multiplicity in the backward hemispheres b. Data denoted by full circles were obtained with all tracks of each event included. Particles within a gap $|y| < 0.75$ were excluded to obtain the data denoted by the open circles. (b) The ratio of the forward-backward multiplicity fluctuation, $\langle (f-b)^2\rangle$, to the multiplicity of negative particles, n_-, for different topologies. The solid curve is a result of a Monte Carlo calculation (Ref. 19). The dashed line marks the value of the plotted variable which was used to estimate the value of the Δ parameter.

[*] Work supported in part by the National Science Foundation.

[†] Work supported by the U. S. Atomic Energy Commission.

[‡] Operated by Universities Research Association, Inc. under contract with the U. S. Atomic Energy Commission.

[1] Details of event reconstruction are given in Y. Cho *et al.*, Phys Rev. Lett. 31, 413 (1973); R. Singer *et al.*, Phys. Lett. 49B, 481 (1974).

[2] J. Whitmore, in *Experiments on High Energy Particle Collisions—1973,* AIP Conference Proceedings No. 12, edited by R. S. Panvini (American Institute of Physics, New York, 1973), p. 14; G. Belletini, in *Proceedings of the Sixteenth International Conference on High Energy Physics, The University of Chicago and National Accelerator Laboratory, 1972,* edited by J. D. Jackson and A. Roberts (National Accelerator Laboratory, Batavia, Ill., 1973), Vol. 1; D. Sivers and G. Thomas, ANL Report No. ANL/HEP 7321 (to be published), and Phys. Rev. D 9, 208 (1974).

[3] C. M. Bromberg *et al.*, Phys. Rev. D 9, 1864 (1974).

[4] Singer *et al.*, Ref. 1.

[5] S. Nussinov *et al.*, Phys. Rev. D 6, 2713 (1972).

[6] About 80% (40%, 10%) of the cross section for $n = 2$ (4, 6) in 205-GeV/c pp interactions are diffractively produced. S. J. Barish *et al.*, Phys. Rev. Lett. 31, 1080 (1973).

[7] Aachen-Berlin-CERN-London-Vienna Collaboration, CERN Report No. D.Ph.II/PHYS 73-18 (to be published).

[8] A. W. Chao and C. Quigg, Phys. Rev. D 9, 2016 (1974).

[9] Protons with $x = 2p_l^{\text{c.m.}}/\sqrt{s} < -0.6$ were identified by ionization. Positive particles with $x > +0.6$ were taken to be leading protons.

[10] A. Białas, CERN Report No. Ref. Th. 1745-CERN (to be published). Data from the Bonn-Hamburg-München Collaboration.

[11] T. T. Chou and C. N. Yang, Phys. Rev. D 7, 1425 (1973).

[12] C. Quigg and G. H. Thomas, Phys. Rev. D 7, 2752 (1973).

[13] F. T. Dao and J. Whitmore, Phys. Lett. 46B, 252 (1973); E. L. Berger *et al.*, Phys. Rev. D 7, 1412 (1973).

[14] T. Ludlam *et al.*, Phys. Lett. 48B, 449 (1974).

[15] E. L. Berger and G. C. Fox, Phys. Lett. 47B, 162 (1973); R. Slansky, Nucl. Phys. B73, 477 (1974).

[16] M. Pratap *et al.*, Phys. Rev. Lett. 33, 797 (1974).

[17] C. J. Hammer and R. F. Peierls, Phys. Rev. D 8, 1358 (1973).

[18] This value depends on the assumed charged multiplicity 2 in the "ω" cluster. The studies done in Refs. 14 and 15 suggest slightly higher multiplicities. We use here the "ω" cluster model only as a simple reference model for indpendent-cluster emission.

[19] We use transverse-momentum damped phase space and a Poisson multiplicity distribution with the observed mean in 205-GeV/c pp interactions.