Observation of a Universal Charge-Exchange Dependence across Rapidity Gaps in 200-GeV/c $\pi^- p$ Interactions*

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Direct evidence is presented showing a universal decrease of charge exchange $|\Delta Q| > 1$ as a function of rapidity-gap length, independent of multiplicity and rapidity position within an event. The region over which charge exchange does occur (the "charge-mobility length") is 1.3 rapidity units.

Considerable evidence has accumulated in favor of local charge compensation in high-energy multiparticle production.[1] This suggests something like a multiperipheral picture. It is of interest to test this conjecture and to elicit the details of such a mechanism. To this end we have studied charge exchange across rapidity gaps in our 200-GeV/c $\pi^- p$ data.

We would expect the charge exchange between adjacent particles in a multiperipheral chain to be limited to $|\Delta Q| \leq 1$. One does of course observe $|\Delta Q| > 1$ between particles adjacent in rapidity. We investigate the extent to which this can be explained as a local departure from strong ordering, consistent with an underlying multiperipheral mechanism. We also study the homogeneity of the multiperipheral chain (independence of distance from the ends), and we look for possible dynamical differences between neutral and charged links.

Approximately 160 000 sets of bubble- and spark-chamber photographs were taken with the Fermilab 30-in. bubble-chamber, wide-gap spark-chamber, hybrid spectrometer.[2] The data reported here consist of approximately 10 000 inelastic events of all topologies.[3]

In the present analysis, the charged particles of each event are ordered in rapidity (i.e., $y_i < y_{i+1}$) such that the nth rapidity gap is given by $\Delta y_n = y_{n+1} - y_n$, and the charge exchange across the nth rapidity gap, ΔQ_n, is defined as

$$\Delta Q_n = \left(\sum_{i=1}^{n} Q_i\right) - Q_T,$$

where Q_i is the charge of the ith particle and Q_T is the charge of the target. Thus for an N-prong event there are $N-1$ gaps each associated with a charge exchange ΔQ. The main concern of this paper is to study the behavior of ΔQ as a function of Δy. In addition, we examine the dependence of ΔQ both on the rapidity-gap position in the event and on the charged-particle multiplicity, N.

We begin by noting that for adjacent rapidity gaps the charge exchange must differ by one unit, and also that for end gaps the charge exchange must be even ($|\Delta Q|_{\text{end gap}} = 0$ or 2). As a result, ΔQ alternates between even and odd values along the rapidity chain. This is illustrated in Figs. 1(a) and 1(b), which represent two possible events, one with $|\Delta Q|$'s restricted to values < 2, and the other event with no apparent restriction on ΔQ. Most high-energy models predict the suppression of large ΔQ; in particular, for multiperipheral models one might expect the dominance of $I = 0$ and $I = 1$ exchange to lead to $\Delta Q = 0$ and $\Delta Q = \pm 1$ gaps. One would not expect the occurrence of $|\Delta Q| > 1$ gaps in the strong-ordering limit, as illustrated in Fig. 1(a). However, for small Δy the strong ordering would be violat-

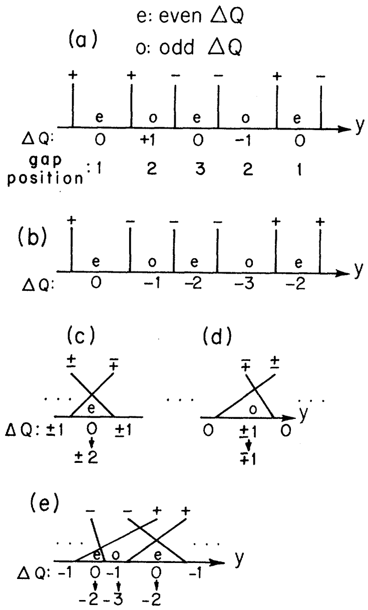

FIG. 1. Illustration of an event with charged particles represented by vertical lines at various values of rapidity (a) for $|\Delta Q|$'s < 2; (b) for no restriction on ΔQ. (c) A "crossover" for an even-ΔQ gap. (d) A "crossover" for an odd-ΔQ gap. (e) A multiple crossover.

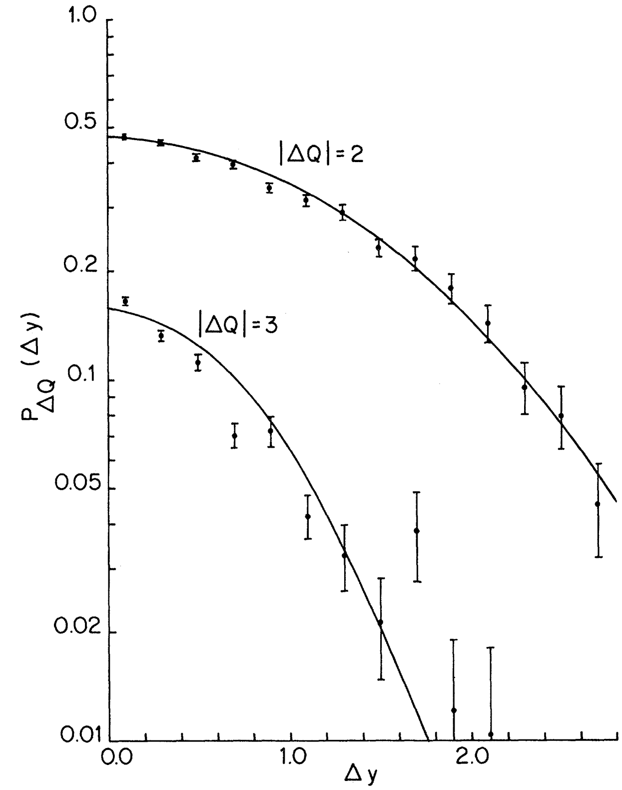

FIG. 2. Probability distributions of $1-P_0(\Delta y)$ for even-ΔQ gaps (labeled $|\Delta Q| = 2$) and $1-P_1(\Delta y)$ for odd-ΔQ gaps (labeled $|\Delta Q| = 3$) as a function of rapidity gap length Δy for inclusive reactions (excluding two-prong events). The curves are Gaussian fits to the data.

ed and "crossovers" such as those shown in Figs. 1(c) and 1(d) would occur, leading to $|\Delta Q|>1$ gaps.[4] For oppositely charged adjacent particles, changes in ΔQ via crossovers would occur as follows: (a) even-ΔQ gaps with $\Delta Q = 0$ would change to $\Delta Q = \pm 2$, and (b) odd-ΔQ gaps with $\Delta Q = \pm 1$ would change to $\Delta Q = \mp 1$. We note that gaps with $|\Delta Q| = 3$ would develop only when a "multiple crossover" involving four particles occurs, as shown in Fig. 1(e). It is thus expected that this multiple crossover would occur with a much smal smaller probability than that for a single crossover.

We now examine the relative ΔQ populations as a function of Δy. In view of the considerations of the previous paragraph, the even-ΔQ gaps and the odd-ΔQ gaps are analyzed separately. We denote the probability for finding ΔQ as $P_{\Delta Q}(\Delta y)$ and normalize, for each Δy bin, the total probability of even-ΔQ and odd-ΔQ gaps to unity:

$$\sum_{\Delta Q \text{ even}} P_{\Delta Q}(\Delta y) = 1,$$

$$\sum_{\Delta Q \text{ odd}} P_{\Delta Q}(\Delta y) = 1.$$

In Fig. 2, we show inclusive distributions (excluding two-prong events) of the quantities $1-P_0(\Delta y)$ and $1-P_1(\Delta y)$. These distributions are nearly identical with $P_2(\Delta y)$ and $P_3(\Delta y)$ since the $|\Delta Q|>3$ populations are negligible. For notational convenience, we refer to these as $|\Delta Q|=2$ and $|\Delta Q|=3$ distributions throughout this paper. In the vicinity of $\Delta y = 0$, one could conclude that nearly 50% of the even-ΔQ gaps have a ΔQ-changing crossover, and approximately 15% of the odd-ΔQ gaps have a multiple crossover. However, as Δy is increased, these percentages decrease rapidly. The solid curves shown in Fig. 2 are fitted Gaussians having widths of 1.32 ± 0.06 rapidity units and 0.75 ± 0.07 rapidity units for the $|\Delta Q|=2$ and the $|\Delta Q|=3$ distributions, respectively. The width of the $|\Delta Q|=2$ distribution is a measure in Δy over which single crossovers occur; we define this width to be the "charge-mobility length." [It is interesting to note that the charge-mobility length has nearly the same value as the two-particle rapidity correlation length (~1.3) determined from the same data.[5]] The width of the $|\Delta Q|=3$ distribution, resulting from multiple crossovers, is more difficult to interpret.

We next consider the charge exchange across

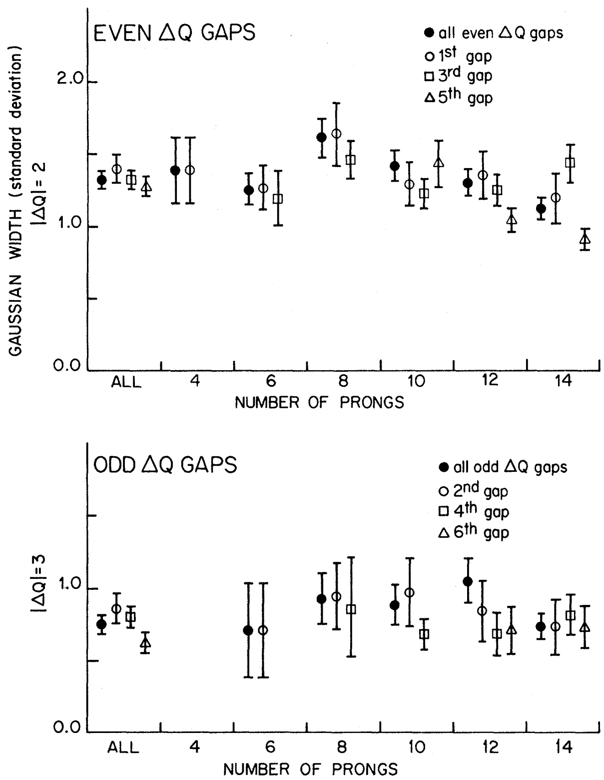

FIG. 3. Widths (in standard deviations) of Gaussian fits to the probability distributions $|\Delta Q| = 2$ and $|\Delta Q| = 3$ in rapidity gap length Δy for inclusive and semi-inclusive reactions and as a function of the gap position.

rapidity gaps for the semi-inclusive channels. Further, for each multiplicity, we determine whether charge exchange depends on the rapidity-gap position within the event. The gap positions are labeled by counting in from the ends of the event as illustrated in Fig. 1(a). (The beam and target ends of the events were also examined separately and were found to be quite similar.) In each of these cases, the procedure outlined above was used to determine the Gaussian widths of the $|\Delta Q| = 2$ distributions (the charge-mobility length); the results are shown in Fig. 3(a). It is seen that the charge-mobility length is *independent of multiplicity and of the gap position within the event.* [It should be noted that a model with randomly emitted charges (but with overall charge conservation) would predict, for semi-inclusive reactions, *no* dependence of ΔQ on the rapidity-gap length.] Furthermore, a similar independence is found for the Gaussian widths of the $|\Delta Q| = 3$ distributions, as shown in Fig. 3(b). These observations imply a certain universality of local charge compensation.

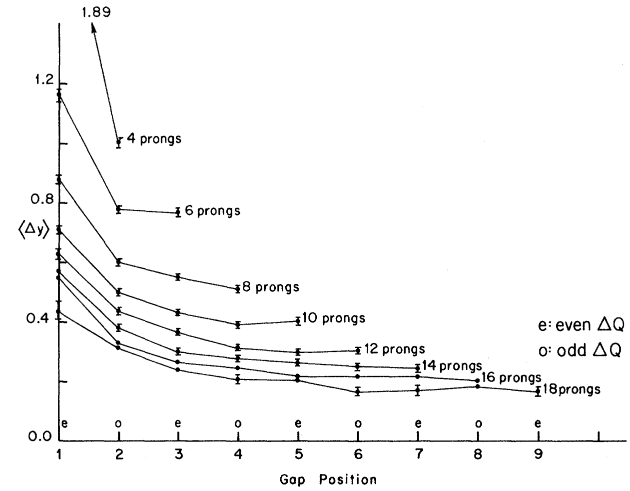

FIG. 4. Mean rapidity gap lengths as a function of multiplicity and gap position.

We now turn to the study of the relative size of gaps with $\Delta Q = 0$ and $|\Delta Q| = 1$; these gaps dominate at large Δy, as seen from Fig. 2. A systematic size difference would imply different dynamical mechanisms for these exchanges. However, it would not be correct simply to compute the gap sizes using directly the observed $\Delta Q = 0$ and $|\Delta Q| = 1$ gap lengths, because the existence of cross-overs would cause greater loss of $\Delta Q = 0$ gaps into $|\Delta Q| = 2$ gaps than of $|\Delta Q| = 1$ gaps into $|\Delta Q| = 3$ gaps. It is therefore more meaningful to compare the size of even-ΔQ gaps with the size of the odd-ΔQ gaps. To this end, we have calculated the mean gap length as a function of multiplicity and gap position (defined as before) within the event. The results are presented in Fig. 4. For all multiplicities there is an increase in mean gap length in going from the center to the end of the event; this behavior could be expected from energy-momentum conservation.[6] The curves drawn through the points show no discernable even-odd oscillation. Such an oscillation would be indicative of a dynamical difference between even- and odd-ΔQ exchanges. Furthermore, with the exception of the lowest multiplicities these curves are quite smooth. For the four-and six-prong events, diffraction would tend to enlarge the first gap.

In summary, our study of the charge exchange across rapidity gaps has revealed the following systematic trends: First, charge exchange with $|\Delta Q| > 1$ is absent at large Δy (strong ordering holds); second, the charge-mobility length (the region in Δy where strong ordering is violated) is found to be ~1.3 rapidity units, independent of multiplicity or rapidity position within an event; finally, we find that the average size of the even-ΔQ gaps (which are mainly $\Delta Q = 0$) and the odd-ΔQ gaps (which are mainly $|\Delta Q| = 1$) are consistent with one another (with the possible exception of the end gap) when viewed as a function of rapidity-gap position within an event. These results, presenting direct evidence of limited charge exchange and an important universality in the dynamics regarding independence of multiplicity and gap position, should provide significant constraints on multiperipheral or other multiparticle production models.

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[1]A. Krzywicki and D. Weingarten, Phys. Lett. 50B, 265 (1974); P. Grassberger, C. Michael, and H. I. Miettinen, Phys. Lett. 52B, 60 (1974); P. Pirilä, G. H. Thomas, and C. Quigg, Phys. Rev. D 12, 92 (1975); C. Bromberg *et al.*, Phys. Rev. D 9, 1864 (1974); T. Kafka *et al.*, Phys. Rev. Lett. 34, 687 (1975); C. Bromberg *et al.*, Phys. Rev. D 12, 1224 (1975); J. Derre *et al.*, "Local Compensation of Charge and Charge Transfer in pp Interactions at 69 GeV/c" (to be published); V. A. Sreedhar *et al.*, "Study of the Charge Structure of Events Produced in 200 GeV/c Collisions" (to be published).

[2]G. A. Smith, in *Particles and Fields—1973*, AIP Conference Proceedings No. 14, edited by H. H. Bingham, M. Davier, and G. R. Lynch (American Institute of Physics, New York, 1973), p. 500.

[3]Particles having no obvious kinks and with momentum greater than 1.5 GeV/c are assumed to be pions. Positive pions with $p < 1.5$ GeV/c are distinguished from protons by ionization. Misidentified protons with $p > 1.5$ GeV/c are shifted in y, but since $\langle n_{\rm ch}\rangle = 8$ and most protons are slow, the background of misidentified protons is only $\simeq 3\%$.

[4]C. E. DeTar, Phys. Rev. D 3, 128 (1971).

[5]N. N. Biswas *et al.*, Phys. Rev. Lett. 35, 1059 (1975).

[6]In addition, it was found that the mean gap lengths at the target and beam ends of the events were nearly the same, with the target end gaps somewhat larger than beam end gaps.

Pion Charge-Exchange Scattering at High Energies*

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We report on a study of pion charge-exchange scattering carried out at Fermilab in the energy range 20 to 200 GeV. The results can be described remarkably well by a simple Regge-pole model. The charge-exchange cross sections in the forward direction lead to a prediction for the difference in total cross sections of $\pi^- p$ and $\pi^+ p$ which is in satisfactory agreement with direct measurements of this difference in another experiment at Fermilab.

In the study of strong-interaction dynamics, two reactions have a special importance because of their simplicity from a theoretical point of view. These are the pion charge-exchange scattering,

$$\pi^- p \to \pi^0 n,$$

and the related reaction in which η mesons are produced,

$$\pi^- p \to \eta n.$$

In Regge theory, the amplitude of each of these reactions is dominated by a single Regge pole (the ρ pole in charge exchange and the A_2 in the η reaction) so that the experimental data have a relatively direct theoretical interpretation. In addition, the forward charge-exchange cross section provides a measure of the difference between $\pi^- p$ and $\pi^+ p$ total cross sections.

With these motivations we have carried out an experiment at Fermilab to study these reactions over a large beam energy range extending from