PHYSICAL REVIEW D VOLUME 16, NUMBER 9 1 NOVEMBER 1977

Evidence for a new general scaling law in strong interactions

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(Received 12 July 1977)

We present evidence in favor of a hitherto unobserved scaling law for strong interactions: the average rest frame of centrally produced secondaries depends only on the charged multiplicity divided by the average charged multiplicity. Evidence in favor of this scaling law is obtained from K^+p data at 5, 8.2, 16, and 32 GeV/c.

It is more and more widely accepted that quarks play an essential role not only in weak and electromagnetic interactions but also in strong interactions. However, the basic mechanism of hadron-hadron collisions is not known. Hence, any experimental regularity which may contain hints concerning the exact interaction mechanism between hadrons is certainly very welcome. Below we present experimental evidence for such a regularity.

It has been known for some time that the average rest frame of centrally produced secondaries in meson-proton interactions is different from the overall center-of-mass frame.[1,2] It was observed that in the rest frame of the centrally produced secondaries the momenta of target and beam particles are in a ratio of approximately $\frac{3}{2}$. This suggested a simple quark interpretation. Indeed this frame is the quark-quark center-of-mass frame if a meson and a nucleon are assumed to be composed of two and three quarks, respectively. However, such a simple interpretation seemed difficult to reconcile with the experimental fact that this asymmetry parameter strongly depends on the multiplicity of the final state.

It was recently suggested[3] that this multiplicity dependence is not in contradiction with the quark idea provided that the average rapidity of centrally produced secondaries obeys a new scaling law, namely, this average rapidity should depend on $(n-1)/\langle n-1\rangle$ only, where n is the number of charge particles in the final state and $\langle n\rangle$ is the average number of charged particles. In this paper we present for the first time experimental evidence in favor of such a scaling law.

There is a simple relation between the average rapidity and the asymmetry parameter R. It is hence equivalent to look for scaling in $\langle y\rangle$ or in R. As usual the asymmetry parameter R is defined as the ratio of the momenta of the incoming particles in the frame where the centrally produced secondaries exhibit forward-backward symmetry. The determination of this parameter is hampered by the possible confusion between genuine centrally produced secondaries and projectile or target fragments. This difficulty is minimized in K^+p or π^+p interactions if only negative secondary particles are used to determine the rest frame of centrally produced particles.

The results presented below are obtained from data on the following reactions:

$$K^+p \to \pi^- + X\,, \quad (1)$$

$$K^+p \to K^0 + \pi^- + X\,. \quad (2)$$

For reaction (1) data are available at 16 and 32 GeV/c and for reaction (2) we use data at 5, 8.2, 16, and 32 GeV/c. Details of all these experiments can be found elsewhere.[4] The number of events used in this analysis is given in Tables I and II. For the present analysis all negative particles were assumed to be pions. Figure 1 shows the c.m. longitudinal momentum of the negative particles for reaction (1). There is no clearly separated contribution of beam or target fragmentation to

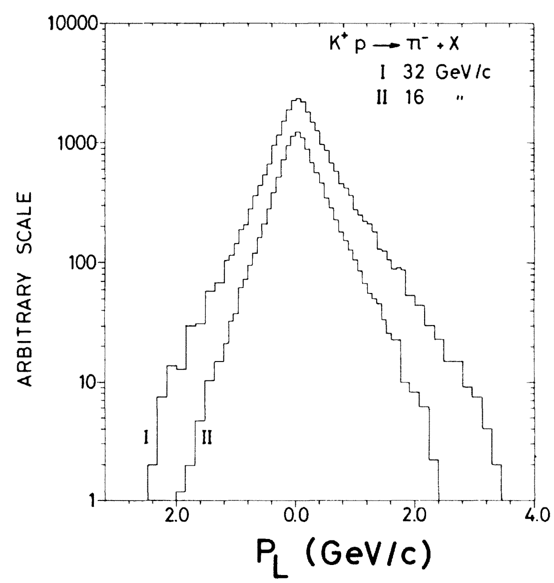

FIG. 1. c.m. longitudinal-momentum distributions for negative particles produced in reaction (1).

TABLE I. Values of R, $\langle y \rangle$, and $\sigma\{y\}$ for different multiplicities for the reaction $K^+p \to \pi^- + X$.

Energy (GeV)	Multiplicity	R	$\langle y \rangle$	$\sigma\{y\}$	No. of events
16	4p	1.773 ± 0.024	0.2770 ± 0.0064	1.0997 ± 0.0033	27970
	6p	1.354 ± 0.016	0.1462 ± 0.0056	0.6179 ± 0.0031	11704
	8p	1.176 ± 0.023	0.0782 ± 0.0092	0.4344 ± 0.0056	2150
	10p	1.166 ± 0.056	0.074 ± 0.023	0.3527 ± 0.0097	229
32	4p	2.102 ± 0.059	0.366 ± 0.014	1.3055 ± 0.0056	8630
	6p	1.551 ± 0.029	0.2158 ± 0.0092	0.7421 ± 0.0041	5981
	8p	1.315 ± 0.026	0.1344 ± 0.0097	0.5121 ± 0.0042	2585
	10p	1.201 ± 0.039	0.090 ± 0.016	0.4078 ± 0.0061	649
	12p	1.107 ± 0.062	0.050 ± 0.027	0.2928 ± 0.0064	115
	14p	1.23 ± 0.11	0.102 ± 0.042	0.186 ± 0.015	14

these distributions, nor to the same distributions for reaction (2) (not shown).

The asymmetry parameter was determined by three different methods, which give compatible results. The first method was a maximum-likelihood fit of an exponential to the longitudinal momentum distribution in the forward and the backward direction. The fit searched for the Lorentz frame where both slopes are equal. The second method consists of determining the average rapidity of all negative pions, which is related to the asymmetry parameter by the relation

$$R = \frac{m_t \sinh(\langle y \rangle - y_t)}{m_b \sinh(y_b - \langle y \rangle)},$$

where m_t, m_b, y_t, and y_b are masses and rapidities of beam and target, respectively. In the c.m. frame this reduces approximately to $R \simeq \exp(2\langle y \rangle)$. Finally the average rapidity of the center of mass of all negative pions produced in each event was determined; it was then related to the asymmetry parameter R by the same formula as before.

For the last method it was checked that the third and fifth central moments of the rapidity distribution vanish. The distribution of the center of mass of all negative particles hence appears to be truly forward-backward symmetric in the frame defined above.

The results obtained with the second method are summarized in Tables I and II. The only important systematic error comes from kaons which have erroneously been interpreted as pions. A K^-/π^- ratio of 0.03 introduces a correction factor of 1.017 in the asymmetry parameter. In the absence of reliable data on this ratio in this energy range, we have not corrected for this effect. The errors quoted are only statistical.

In Fig. 2(a) we display the asymmetry parameter R as a function of the scaling variable $(n-1)/\langle n-1 \rangle$ (Ref. 5) for reaction (1). On Fig. 2 we also

TABLE II. Values of R, $\langle y \rangle$ for different multiplicities for the reaction $K^+p \to K^\circ + \pi^- + X$.

Energy (GeV)	Multiplicity	R	$\langle y \rangle$	No. of events
5.0	4p	1.373 ± 0.065	0.142 ± 0.021	1224
	6p	0.93 ± 0.16	0.034 ± 0.069	26
8.2	4p	1.310 ± 0.042	0.126 ± 0.013	4188
	6p	1.059 ± 0.049	0.027 ± 0.021	547
16	4p	1.519 ± 0.051	0.202 ± 0.016	3672
	6p	1.251 ± 0.042	0.108 ± 0.016	1302
	8p	1.221 ± 0.082	0.096 ± 0.032	169
	10p	1.24 ± 0.27	0.103 ± 0.095	17
32	4p	1.567 ± 0.12	0.221 ± 0.036	929
	6p	1.324 ± 0.075	0.138 ± 0.027	577
	8p	1.197 ± 0.084	0.089 ± 0.034	190
	10p	0.95 ± 0.12	−0.027 ± 0.059	45
	12p	0.86 ± 0.33	−0.07 ± 0.16	6

show the values obtained for reaction (1) at 11.8 GeV/c taken from Ref. 2 and for the reaction $K^-p \to \pi^\pm + X$ taken from Ref. 6. The data clearly scale in this energy range. Moreover K^+ and K^- data appear to lie on the same scaling function. Figure 2(b) shows the same plot for reaction (2). We find again a scaling behavior, but the scaling function is below the one for reaction (1). It can be argued that the scaling variable for reaction (2) should be slightly different from the one for reaction (1). Indeed, the numerator of the scaling variable should probably be proportional to the total number of particles in the final state. The data on reaction (2) are, however, not accurate enough to observe such effects. Data on the reaction $\pi^+p \to \pi^- + X$ are shown in Fig. 2(c). The data are sparse but there is a clear indication of scaling. This scaling behavior hence appears to be a general property of the meson-nucleon interaction.

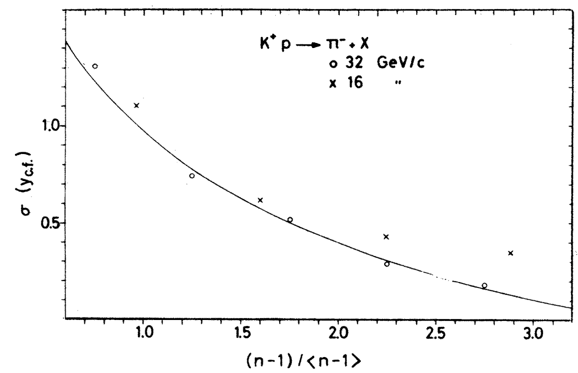

FIG. 3. Width of the rapidity distribution of the center of mass of all negative particles for reaction (1) as a function of $(n-1)/\langle n-1\rangle$. The solid line gives the limiting distribution predicted by the quark model of Ref. 3. The errors have about the size of the dots.

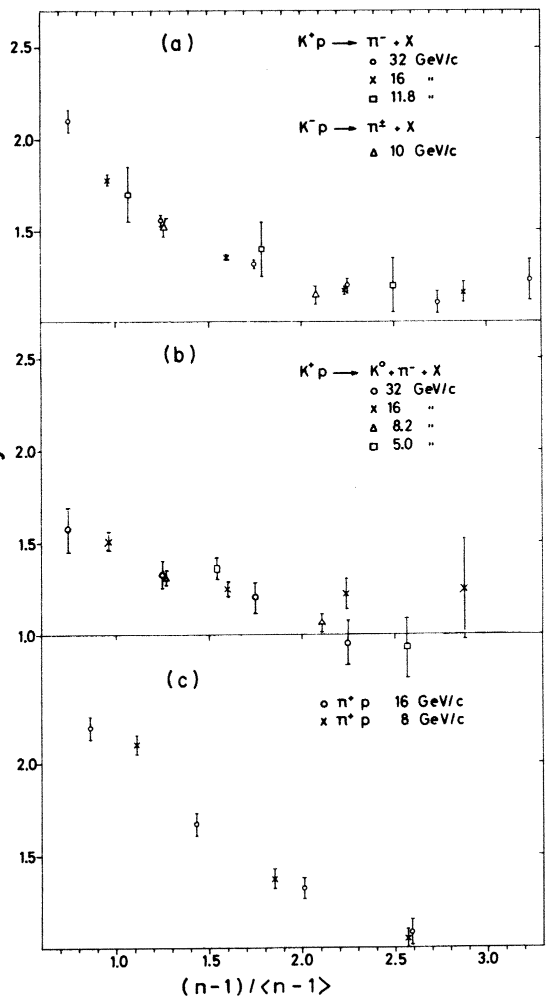

FIG. 2. Asymmetry parameter as a function of $(n-1)/\langle n-1\rangle$ for reactions (1) and (2). For comparison the asymmetry parameter has also been plotted for the reaction $K^-p \to \pi^\pm$ at 10 GeV/c and $\pi^+p \to \pi^- X$ at 8 and 16 GeV/c.

The quark picture suggests using the scaling variable $(n-1)/\langle n-1\rangle$. One may wonder, however, to what extent the data support this particular scaling variable. We have fitted a polynomial $R = A/x + B + Cx$ to the data points with $x = (n-\alpha)/\langle n-\alpha\rangle$, where α was a free parameter in the fit. For reaction (1) we obtain $\alpha = 1.00 \pm 0.14$, with a χ^2 of 2.95 for 6 degrees of freedom. It is interesting to note that in a similar fit to the multiplicity scaling function (Koba-Nielson-Olesen scaling) Wroblewski finds $\alpha = 0.87$ for K^+p reactions.[7] This supports the idea that there is a relation between both scaling laws.

The quark picture predicts the average value and all moments of the rapidity distribution of the central fireball ($y_{\text{c.f.}}$) to scale. Experimentally this prediction is not easy to check for higher moments since only the negative particles of the fireball decay can be used. It may still be useful to study the width of the rapidity distribution. Indeed the true width of the central-fireball rapidity distributions is expected to be smaller than the experimental width. As the energy increases, and hence the number of negative particles for fixed $(n-1)/\langle n-1\rangle$, the experimental distribution should converge slowly from above to the true distribution. If the particles are emitted independently the convergence should go like $\sim\sqrt{n}$. Figure 3 gives the width of the rapidity distribution of the center of mass of all negative particles as a function of the scaling variable for reaction (1). The solid line gives the predicted limiting behavior obtained from the quark picture of Ref. 3. One can see that at 32 GeV/c the data points already reach this limit. This result is difficult to understand in the framework of the simple quark model of Ref. 3.

In conclusion we obtained evidence in favor of a new and general scaling law of strong interactions: The average rapidity of centrally produced secondaries is a function of $(n-1)/\langle n-1\rangle$ only. This scaling law was predicted on the basis of a simple quark model, but the width of the rapidity distribution seems difficult to reconcile with this simple quark idea. The similarity of the best scaling variable for this new scaling and for multiplicity scaling suggests that there is a connection between both scaling laws.

We are grateful to the CERN-Serpukhov-Saclay, and the Brussels-CERN-Birmingham-IPN-Paris-Saclay collaborations for allowing us to use unpublished data, and to Dr. De Wolf and Professor Verbeure for stimulating discussions.

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[4](5 GeV/*c*): W. De Baere *et al.*, Nuovo Cimento 61A, 397 (1969); (8.2 GeV/*c*): G. Charrière *et al.*, Nucl. Phys. B22, 333 (1970); (16 GeV/*c*): G. Ciapetti *et al.*, *ibid.* B64, 58 (1973); (32 GeV/*c*): P. Granet *et al.*, submitted to the Palermo Conference, 1975 (unpublished); Phys. Lett. 62B, 350 (1976).

[5]The following values were used for $\langle n\rangle$: 2.93 ± 0.03 3.38 ± 0.04, 4.12 ± 0.03, and 5.01 ± 0.05 for 5, 8.2, 16, and 32 GeV/*c*, respectively.

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