Theory of Scattering (Prentice-Hall, Englewood Cliffs, New Jersey, 1962).

[2]W. Harrison, *Solid State Theory* (McGraw-Hill, New York, 1970); G. Weinreich, *Solids, Elementary Theory for Advanced Students* (Wiley, New York, 1965).

[3]G. Koster and J. Slater, Phys. Rev. 95, 1167 (1954), and 96, 1208 (1954); M. Lax, Phys. Rev. 94, 1391 (1954). J. Callaway, J. Math. Phys. (N.Y.) 5, 783 (1964), discussed this model as a special case of the general scattering theory of defects.

[4]Some, or all, can be below or above the band depending on signs, strengths, and proximities of the first n defects. We can thus study the formation of "impurity bands" or "energy tails" due to impurity clustering, as a function of the size of the cluster, by our method. See also B. I. Halperin and M. Lax, Phys. Rev. 148, 722 (1966).

[5]The absence of bound states is tantamount to the condition for perturbation theory on the V_j to be correct. This therefore excludes one or two dimensions, in which the infrared divergence in $S^{(0)}(E)$ guarantees that at least one of the $Q^{(n)} \neq 0$, viz., $Q^{(0)}=1$, regardless of the sign or strength of V_1. Thus perturbation expansions would appear to be valid only in three or higher dimensions.

Nucleon-Number Dependence of the Production Cross Sections for Massive Dihadron States

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We have measured the nucleon-number (A) dependence of the production cross sections for dihadron states in which each hadron is required to have large transverse momentum. We find that the A dependence varies with the total dihadron transverse momentum in a manner similar to that previously observed for single hadrons.

For several years the nucleon-number (A—also called atomic weight) dependence of hadron production at large transverse momentum ($p_\perp$) has posed intriguing questions.[1-3] The fact that single-hadron production cross sections vary as A^α with $\alpha>1$ implies that the nucleus must act collectively in producing a single hadron at high $p_\perp$. Perhaps the simplest collective mechanism is multiple scattering within the target nucleus.[4-9] More exotic mechanisms include the collective motion of nucleons[10,11] as well as the collective or energetic motion of partons[5,12]—motions which must change as a function of A.

In this experiment we observe two high-$p_\perp$ hadrons coming from the same interaction. They are detected in a double-arm magnetic spectrometer[13] equipped with Čerenkov particle identification and hadron calorimeter background rejection. We study collisions of 400-GeV/c protons with tungsten (W) and beryllium (Be) nuclei and observe interactions which produce two hadrons emitted back to back at ~90° in the proton-nucleon center of momentum. If $p_{\perp+}$ denotes the magnitude of the transverse momentum of the positive member of a hadron pair of net charge zero, it is convenient to define the following two quantities:

$$m' \equiv p_{\perp+} + p_{\perp-}, \qquad p_{\perp N} \equiv p_{\perp+} - p_{\perp-}.$$

The net transverse momentum of the pair is approximately equal to $p_{\perp N}$. [Since our azimuthal acceptance for each hadron is very small (~0.1 rad) we neglect the vector nature of transverse momentum.] Then dihadron $p_\perp$ (magnitude implied) is given by $|p_{\perp N}|$. For a pair with small dihadron $p_\perp$, m' closely approximates the mass of the dihadron system.

The data presented here were obtained using several redundant triggers. Calorimeter signals,[13] proportional to total hadron energy in each arm, were weighted according to (scintillation-counter) production-angle information in order to construct analog signals proportional to single-hadron $p_\perp$. The high-mass (HM) trigger utilized the sum of these two $p_\perp$ signals to require m' to be greater than a preset threshold. Alternative calorimeter pair trigger requirements were formed from the coincidence of single-arm requirements triggered by single-hadron $p_\perp$ or by single-hadron total energy. If T_1 denotes a track (coincidence of three scintillation counters) in arm 1, then the pair trigger consisted of $(T_1 \cdot T_2)$ in coincidence with HM or one of the alternative pair requirements.

In analogy with the case of single hadrons, we assume that the dihadron invariant production cross sections for protons incident on a nucleus containing A nucleons are proportional to A^α. We then measure $\alpha_{\rm pair}$ using Be and W targets. The luminosity was monitored by a four-counter telescope (N) placed in the neutral beam of one of the spectrometer arms. (A neutral beam was formed downstream from each analyzing magnet by the deflection of charged particles.) The target-in/target-out ratio for this monitor was typically 50/1. The N rate was linear versus incident beam intensity as measured by a secondary-emission monitor (SEM) up to rates over twice those used during the experiment. Our targets were horizontally narrow (0.22-mm Be and 0.42-mm W) but a large fraction of the incident beam (typically 70% for Be, 95% for W) intercepted the target. The calibration of N/SEM for protons intercepting the target was carried out through the use of horizontal target scans. This calibration repeated within an accuracy of 5% over the course of the experiment and was checked for Be with the use of a wide (2.0-mm) target. Vertically our targets (>6 mm high) were much larger than the beam (~0.8 mm high, full width at half-maximum). The target lengths were 103 mm for Be and 13 mm for W.

If n represents the number of events detected, we define the W/Be yield ratio

$$Y = (n/N)_{\rm W}/(n/N)_{\rm Be}$$

and calculate α according to the prescription

$$\alpha = \ln(CY)/\ln(A_{\rm W}/A_{\rm Be}),$$

where $C = 11.7$ for our target-monitor system.[14] Corrections have been made for absorption of incident protons and secondaries in both targets. Approximately 13% of the pair events are lost from these mechanisms with either target. The effects of the difference in multiple scattering between our tungsten and beryllium targets are negligible.

We have monitored our W/Be relative efficiencies from the repeatability of our single-hadron yields as well as from direct efficiency measurements. Stability of the data triggers was monitored throughout our A-dependence measurements by the use of special runs with less restrictive triggers. The efficiencies of proportional wire chambers (PWC) and scintillation counters not required in the trigger were monitored during data taking. Corrections for small efficiency changes (~10% in Y) have been made to the data. We estimate our total single-arm systematic uncertainty to be ±0.03 in α, arising from uncertainties in both relative normalization and relative efficiency.

Since we wish to study correlated hadron pairs, arm-to-arm accidental coincidences (originating from two separate but simultaneous interactions in the target) were subtracted from the pair yields. The coincidence rate $(T_1 \cdot T_2)$ was observed to vary as the square of the incident beam intensity (±10%) and was used to normalize spectra of uncorrelated pairs generated by combining spectra of single-arm triggers (recorded simultaneously with the pairs). The resulting fraction of accidental pairs amounted typically to 40% of the total for W and 20% for Be for a 1-GeV/c bin in m' just above threshold. The fraction of events subtracted decreases rapidly as m' increases (factor of 2 decrease for 1 GeV/c increase in m') but does not vary strongly with dihadron $p_\perp$. Data were taken with thresholds ranging from $m' = 4.5$ to $m' = 6.5$ GeV/c with corresponding adjustments of the beam intensity over a factor of 5 (between 2×10^9 and 10^{10} incident protons per second). All data samples and all triggers yield consistent results. In addition, the subtraction has been checked for m' well below threshold where essentially all of the pairs are accidental. Consequently we believe that we can perform the subtraction of accidental pairs to an accuracy of 20% of itself.

We estimate our total systematic uncertainty from all the above effects to be ±0.06 in α for pairs. In the data that follow, the quoted errors are purely statistical since point-to-point comparisons are largely free of the systematic uncertainties.

In Fig. 1 we show α values for dihadrons (without regard to particle identification) as a function of $p_{\perp+}$ and $p_{\perp-}$. For single-hadron $p_\perp$ values less than 1 GeV/c we do not accept hadrons into our apparatus; so we use the corresponding locations

$P_{\perp -}$ (GeV/c)

1.14 ±0.21	1.34 ±0.23	1.20 ±0.13	0.52 ±0.41	1.41 ±0.27		
1.16 ±0.05	1.08 ±0.11	1.04 ±0.07	1.11 ±0.09	1.17 ±0.17		
1.11 ±0.01	1.14 ±0.07	0.98 ±0.05	0.89 ±0.05	0.90 ±0.10	1.12 ±0.17	
1.03 ±0.01		1.01 ±0.04	1.00 ±0.05	0.95 ±0.08	1.16 ±0.12	1.65 ±0.33
0.97 ±0.01			1.01 ±0.08	1.07 ±0.11	1.50 ±0.20	0.81 ±0.68
SINGLE	0.97 ±0.01	1.06 ±0.01	1.12 ±0.01	1.09 ±0.03	0.94 ±0.16	1.33 ±0.47

$P_{\perp +}$ (GeV/c)

FIG. 1. The powers α of the A dependence of the invariant cross sections for production of dihadrons and single hadrons are given as a function of $p_{\perp +}$ and $p_{\perp -}$.

in Fig. 1 to display our single-hadron α values measured simultaneously with the pair values. Near the center of the plot the pair α values are low. In particular, if we require a positive hadron with $p_{\perp +}$ between 3 and 4 GeV/c in addition to a negative hadron between the same $p_\perp$ limits, α drops by 0.22 ± 0.07 relative to the value for the negative hadron alone. (Here we include a systematic uncertainty of 0.05 for the random pair subtraction.) This change in α corresponds to a factor-of-2 drop in Y relative to what one would expect if pair and single-arm α values were equal.

In Fig. 2 we rebin the data from Fig. 1 and examine the dependence of α on m' and dihadron $p_\perp$. If we integrate over all $p_{\perp N}$, α is flat versus m' and consistent with 1. We note, however, that α rises significantly above 1 for dihadron $p_\perp$ values greater than 2 GeV/c. This is especially evident for high m' where large $p_\perp$ values are accessible. We compare the results to our single-hadron α values and to previously measured[15] single-hadron values also plotted versus $p_\perp$. The hadron and dihadron A dependences show similar increases in α at high $p_\perp$. Thus it appears that the transverse momentum delivered to the final state determines the A dependence of the production of that state for states of two hadrons emerging back to back in the center of momentum after a hard collision as well as for single-particle states.

In Fig. 3 we show the variation of α with the species of the final state. Since α does not vary strongly as a function of m' we integrate over all

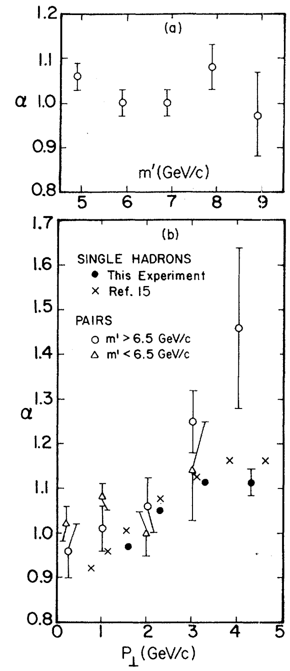

FIG. 2. The power α of the A dependence of the invariant dihadron production cross section is plotted (a) as a function of m' for all $p_\perp$ and (b) as a function of $p_\perp$ for $m' < 6.5$ GeV/c and for $m' > 6.5$ GeV/c. Comparison is made to the single-hadron A dependence. Statistical errors are shown when they are larger than the symbols representing the data points.

m' above threshold and display separately α for $p_\perp$ less than and greater than 2.1 GeV/c. Unfortunately because our pair identification efficiency is concentrated near dihadron $p_\perp = 0$, we cannot make definite statements regarding the species

	π^-	K^-	$\bar{P}$	h^-
π^+	0.99±0.03 1.08±0.11	1.05±0.09 1.37±0.46	1.29±0.14 —	1.00±0.03 1.12±0.08
K^+	0.98±0.09 —	1.33±0.17 —	— —	1.05±0.06 1.24±0.22
P	1.11±0.07 —	1.58±0.21 —	1.37±0.13 —	1.16±0.05 1.14±0.19
h^+	1.00±0.02 1.15±0.06	1.11±0.06 1.52±0.20	1.17±0.07 1.41±0.43	1.01±0.02 1.18±0.04

FIG. 3. The power α of the A dependence of the invariant dihadron production cross section is given as a function of particle species for $p_\perp < 2.1$ GeV/c (upper value in each box) and for $p_\perp > 2.1$ GeV/c (lower value in each box). h^+ denotes all positive hadrons.

dependence of the rise in $\alpha_{\rm pair}$ vs $p_\perp$. We can, however, see significant species dependence of α at low dihadron $p_\perp$. The values of α are especially high for pK^- and $p\bar{p}$ states, which contain two particles, each with a single-hadron α value which reaches 1.3 at high $p_\perp$.

In conclusion, we find that the dihadron A dependence in the hard-scattering region exhibits a behavior as a function of $p_\perp$ similar to that observed for single hadrons. But, with integration over all $p_\perp$, the average $\alpha_{\rm pair}$ is consistent with 1 for $m' > 4.5$ GeV/c. As was evident from single-hadron results,[1] the quantum numbers of the state produced play an important role.

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[1]L. Kluberg *et al.*, Phys. Rev. Lett. 38, 670 (1977).

[2]L. M. Lederman, in *High-Energy Physics and Nuclear Structure—1975*, AIP Conference Proceedings No. 26, edited by H. C. Wolfe (American Institute of Physics, New York, 1975), p. 303.

[3]U. Becker *et al.*, Phys. Rev. Lett. 37, 1731 (1976).

[4]J. Pumplin and E. Yen, Phys. Rev. D 11, 1812 (1975).

[5]G. Farrar, Phys. Lett. 56B, 185 (1975).

[6]P. V. Landshoff, J. C. Polkinghorne, and D. M. Scott, Phys. Rev. D 12, 3738 (1975).

[7]P. M. Fishbane and J. S. Trefil, Phys. Rev. D 12, 2113 (1976); P. M. Fishbane, John K. Kotsonis, and J. S. Trefil, Phys. Rev. D 16, 122 (1977).

[8]J. H. Kühn, Phys. Rev. D 11, 2948 (1976).

[9]M. L. Good, Y. Kazama, and C. N. Yang, Phys. Rev. D 15, 1920 (1977).

[10]G. Berlad, A. Dar, and G. Eilam, Phys. Rev. D 13, 161 (1976).

[11]S. Fredriksson, Nucl. Phys. B111, 167 (1976).

[12]A. Krzywicki, Phys. Rev. D 14, 152 (1976).

[13]R. D. Kephart *et al.*, Phys. Rev. Lett. 39, 1440 (1977).

[14]If $k \equiv$ (N/SEM) $\times$ [A/(Avogadro's number $\times$ density of target $\times$ length of target)], then $C = k_{\rm W}/k_{\rm Be}$.

[15]We calculate α for hadrons (averaged over charge) using α values for π, K, and p from Ref. 1 and particle ratios from J. W. Cronin *et al.*, Phys. Rev. D 11, 3105 (1975).

Search for Fractionally Charged Tungsten Ions

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A search for W ions having an additional charge of $-\frac{1}{3}e$ has been conducted, using a Van de Graaff accelerator as an ultrasensitive mass spectrometer. The study investigated masses varying from 182 to 192 amu. No evidence was found for the existence of such ions to a limit of 1 part in 1×10^{12} over the mass range covered.

Since the original suggestion by Gell-Mann[1] and Zweig[2] that particles with fractional charge may exist, several groups have searched for such particles (quarks) either by attempting to produce them in accelerators,[3] or by detecting their presence in cosmic rays or in various materials in which they may be trapped.[4] Searches for integrally charged quarks[5] which would manifest themselves as stable particles of anomalous mass have also been reported.[6] All such searches have been negative except for a recent result from a magnetic levitation experiment reported by LaRue, Fairbank, and Hebard.[7] That result suggests[8] that the quarks are attached to W atoms or nuclei, producing fractionally charged W (hereafter denoted as W_f). A more recent result by Bland *et al.*[9] finds no evidence for fractional charge in W at a sensitivity of 1 part in 1.1×10^{12}.

The present experiment involves quite a different approach. The tandem Van de Graaff accelerator facility of the University of Rochester Nuclear Structure Research Laboratory was used as a double mass spectrometer followed by a detection system [see Fig. 1(a)]. The entire system was designed to accept W_f in a specific charge state, the $W_f^{+14/3}$ state, and to reduce the intensities of other ionic species as much as possible.

The accelerator injection system, consisting of a sputter ion source,[10] inflection magnet, and 150-kV preacceleration column, selects negative