Observation of Color-Transparency in Diffractive Dissociation of Pions

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(Received 18 October 2000)

We have studied the diffractive dissociation into dijets of 500 GeV/c pions scattering coherently from carbon and platinum targets. Extrapolating to asymptotically high energies (where $t_{\min} \to 0$), we find that when the per-nucleus cross section for this process is parametrized as $\sigma = \sigma_0 A^\alpha$, α has values near 1.6, the exact result depending on jet transverse momentum. These values are in agreement with those predicted by theoretical calculations of color-transparency.

DOI: 10.1103/PhysRevLett.86.4773 PACS numbers: 14.40.Aq, 25.80.Ek

Color transparency (CT) is the name given to the prediction that the color fields of QCD cancel for physically small singlet systems of quarks and gluons [1]. This color neutrality (or color screening) should lead to the suppression of initial and final state interactions of small-sized systems formed in hard processes [2], often referred to as pointlike configurations (PLC's). Observing color transparency requires that a PLC is formed and that the energies are high enough so that expansion of the PLC does not occur while traversing the target [3–5] (the "frozen" approximation). To demonstrate that the interactions of a PLC with the nucleons in a nucleus are suppressed compared to those of ordinary hadrons requires identifying observables which depend explicitly on the cross sections of the PLC's. Measurements of color transparency are important for clarifying the dynamics of bound states in QCD [6,7].

Perturbative QCD predicts that a PLC is formed in many two-body hadronic processes at very large momentum transfer [2,8]. Experimental studies of such processes have failed to produce convincing evidence of color transparency [9–11]. However, the momentum transfer may not have been high enough and/or the frozen approximation not valid under these experimental conditions. Evidence for color transparency (small hadronic cross sections) has been observed in other types of processes: in the A dependence of J/ψ photoproduction [12], in the Q^2 dependence of the t slope of diffractive ρ^0 production in muon scattering [13] (where Q^2 is the invariant mass of the virtual photon and t denotes the negative square of the momentum transfer from the virtual photon to the target proton), in the yield of nondiffractive ρ^0 production in deep inelastic muon scattering [14], and in the energy and flavor dependences of vector meson production in ep scattering at DESY ep collider HERA [15]. In this paper, we report a direct observation of color transparency in the A dependence of diffractive dijet production by pions.

The pion wave function can be expanded in terms of Fock states:

$$\Psi = \alpha|q\bar{q}\rangle + \beta|q\bar{q}g\rangle + \gamma|q\bar{q}gg\rangle + \ldots. \qquad (1)$$

The first (valence) component is dominant at large Q^2. The other terms are suppressed by powers of $1/Q^2$ for each additional parton, according to counting rules [16,17]. When the relative velocities of all participating particles are nearly lightlike, time dilation lengthens the lifetimes of these states and "freezes" the partonic content of the pion "seen" by the other particles. Bertsch *et al.* [18] proposed that when high momentum pions hit a nuclear target, the physically small $|q\bar{q}\rangle$ components will be filtered by the nucleus and materialize as diffractive dijets. In a more recent calculation, based on a generalization of the QCD factorization theorem, Frankfurt *et al.* [19] proposed that these small $|q\bar{q}\rangle$ components can scatter coherently from nuclei producing high mass dijets. When the transverse momentum of the individual jets with respect to the beam direction (k_t) is large, the mass of the dijet must also be large. Frankfurt *et al.* show that for $k_t > 1.5$ GeV$/c$ the interaction with the nucleus is completely coherent and $\sigma(|q\bar{q}\rangle\mathcal{N} \rightarrow \text{dijets } \mathcal{N})$ is small. This leads to an A^2 dependence of the forward amplitude squared for asymptotically high energies (where $t_{\min} \rightarrow 0$).

As a good approximation, the integrated *per-nucleus* cross section for producing these high mass dijets grows as $A^{4/3}$. The forward amplitude squared provides a factor of A^2 [19] and the integral of the elastic-scattering form factor, $\approx\int \exp(-\beta R_0^2 t)\, dt$, contributes a factor $A^{-2/3}$ (on the assumption that $R_0 \approx A^{1/3}$ and β, which depends on nuclear density, is the same for all targets). This should be compared with $\sigma \propto A^{2/3}$ typical of normal pion-nucleus interactions (for which the shadowing cross section is approximately the full π-$\mathcal{N}$ inelastic cross section). Using more realistic nuclear form factors and accounting for higher twist effects will change the A dependence modestly, and electromagnetic contributions should produce negligible effects [20].

In this Letter we report measurements of the A dependence of the diffractive dissociation into dijets of 500 GeV$/c$ pions scattering coherently from carbon and platinum targets using data from Fermilab experiment E791. We recorded $2 \times 10^{10}\pi^-$-nucleus interactions during the 1991/1992 fixed-target run at Fermilab using an open geometry spectrometer [21] in the Tagged Photon Laboratory. The segmented target consisted of one platinum foil and four diamond foils separated by gaps of 1.34 to 1.39 cm. Each foil was approximately 0.4% of an interaction length thick (0.5 mm for platinum and 1.6 mm for carbon). Six planes of silicon microstrip detectors (SMD) and eight proportional wire chambers (PWC) were used to track the beam particles. The downstream detector consisted of 17 planes of SMDs for vertex detection, 35 drift chamber planes, 2 PWCs, 2 magnets for momentum analysis, 2 multicell threshold Cerenkov counters (not used in this analysis), electromagnetic and hadronic calorimeters for electron identification and for online triggering, and two planes of muon scintillators. An interaction trigger required a beam particle and an interaction in the target. A very loose transverse energy trigger, based on the energy deposited in the calorimeters, and a fast data acquisition system allowed us to collect data at a rate of 30 Mbyte/s with 50 μs/event dead time and to write data to tape at a rate of 10 Mbyte/s.

Data reconstruction and additional event selection were done using offline parallel processing systems. The data for this analysis are selected with the primary requirement that at least 90% of the beam momentum is carried by charged particles. This reduces the effects of unobserved neutral particles. In addition, this analysis uses events produced relatively early in the experiment, before the performance of the drift chambers degraded in the region through which the pion beam passed. The offline selection for this analysis was implemented after most of the data had already been filtered for other analyses, and we use data taken only when all five targets were in place. In all, about 10% of the experiment's integrated data set is used in this analysis.

The JADE jet-finding algorithm [22] is used to identify two-jet events. The algorithm's cutoff parameter (m_{cut}) was optimized for this analysis by using Monte Carlo (MC) simulations which are described below. For each two-jet event we calculate the transverse momentum of each jet with respect to the beam axis (k_t), the transverse momentum of the dijet system with respect to the beam axis (q_t), and the dijet invariant mass, M_J. The dijet invariant mass is related to the quarks' longitudinal momentum fractions in the pion infinite momentum frame (x) by simple kinematics: $M_J^2 = k_t^2/[x(1-x)]$. To ensure clean selection of high mass dijet events, a minimum k_t of 1.2 GeV$/c$ is required. The selection of clean dijet events was verified by testing their relative azimuthal angle which for pure dijets should be near 180°. This angle is required to lie within 20° of this value. The size of a $|q\bar{q}\rangle$ system which produces dijets with $k_t > 1.5$ GeV$/c$ can be estimated as $1/Q \le 0.1$ fm, where $Q^2 \sim M_J^2 \ge 4k_t^2 \sim 10$ GeV$^2/c^2$. The distance that the $|q\bar{q}\rangle$ system travels before it expands appreciably, the coherence length, is given by $\ell_c \sim (2p_{\text{lab}})/(M_J^2 - m_\pi^2)$ [3] which is $\sim$10 fm for $M_J \sim 5$ GeV$/c^2$. Therefore, we expect that the dijet signal events selected in this analysis evolve from pointlike configurations which will exhibit color transparency.

The q_t^2 distributions of the selected dijet events are shown in Fig. 2 below and in Fig. 1 of [23]. The peaks at small q_t^2 arising from coherent scattering from nuclei are smeared due to missing neutrals and detector resolution, but the integrated coherent signals can be extracted with reasonable accuracy. Before detector acceptance and smearing, coherent peaks should be produced with $dN/dq_t^2 \propto \exp(-bq_t^2)$ with b inversely proportional to the nucleus' radius (2.44 fm for carbon and 5.27 fm for platinum [24]). Because theory predicts that the A dependence varies with k_t [19], the analysis is carried out in three k_t regions: $1.25 \leq k_t \leq 1.5$ GeV/c, $1.5 < k_t \leq 2.0$ GeV/c, and $2.0 < k_t \leq 2.5$ GeV/c. Altogether, we find about 5000 coherent dijet events in the carbon data set and about 2800 in the platinum data set.

To determine the relative number of coherent events produced in each target, we fit the data as sums of q_t^2 distributions of dijet events produced coherently from nuclear targets, dijet events produced coherently from individual nucleons but incoherently with respect to the nuclear targets, and background. The shapes of the dijet distributions are calculated using Monte Carlo simulations. We use the LUND PYTHIA-JETSET package [25] to generate dijet events with masses of 4, 5, and 6 GeV/c^2. This covers the range of k_t observed in the data. The quark momentum distribution inside the pions is generated using an asymptotic wave function [26,27] which is consistent with the data presented in our companion paper [23]. Coherent nuclear events are generated with q_t^2 slopes appropriate to carbon and platinum. Coherent nucleon events are generated with q_t^2 slopes appropriate to the nucleon radius (0.8 fm), truncated at $q_t^2 = 0.015$ (GeV/c)^2 to account for the nucleon binding energy. The generated events are passed through a detector simulation and digitized to mimic real events. They are reconstructed and analyzed using the same programs used to reconstruct and analyze the real data.

To determine the relative efficiencies for observing dijet events produced through coherent diffractive scattering from carbon and platinum nuclei, we use Monte Carlo samples generated with dijet masses of 4, 5, and 6 GeV/c^2. The proportions are adjusted to reproduce the k_t spectrum of the data, as observed in Fig. 1. For each k_t range, and for each target, we fit the q_t^2 distribution by using the signal shapes from the Monte Carlo simulations and by assuming that the background contribution is linear in q_t^2. Figure 2 shows the results of the fit for $1.5 \leq k_t \leq 2.0$ GeV/c. The dotted lines show the coherent nuclear distribution, the dashed line the coherent nucleon/incoherent nuclear distribution, and the dash-dotted lines the residual background. This background represents the components of the data which are not simulated well, such as badly identified jets. The background's contribution in the region of the coherent distribution is small. These fits provide normalization factors between the number of simulated events of each type and the data.

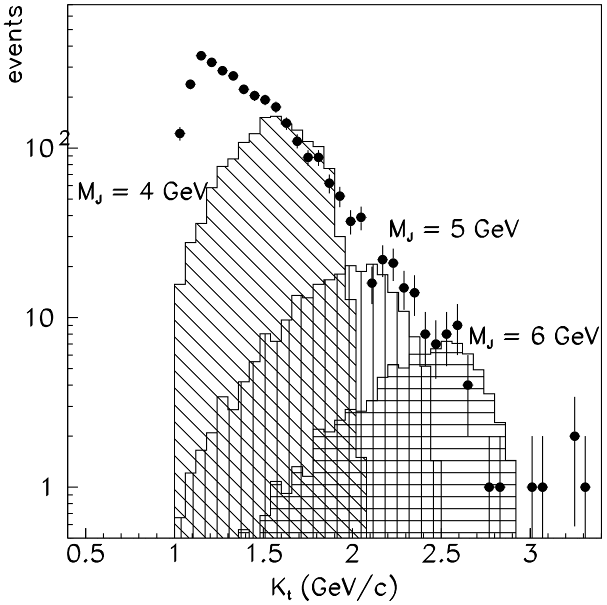

FIG. 1. k_t distributions of simulated dijets with 4 (slanted lines), 5 (vertical lines), and 6 (horizontal lines) GeV/c^2 masses normalized and superimposed on the distribution from data taken with a platinum target.

We derive the relative numbers of produced dijet events for each target in each k_t bin by integrating over the diffractive terms in the fits and accounting for the relative efficiencies as described above. The signals from the carbon and platinum targets in any one k_t range have slightly different mass distributions, and we correct the relative yields to account for this. Using the measured target thicknesses, we determine the ratio of cross sections for coherent production of diffractive dijets from the carbon and platinum targets (which received essentially the same beam flux). Theoretical calculations of color transparency at asymptotically high energies predict $\sigma = \sigma_0 A^\alpha$ with $\alpha = 4/3$ assuming very simple nuclear wave functions. At the energy of this experiment, $|t_{\min}| > 0$ reduces the cross sections for coherent scattering on carbon (platinum) targets to 0.98 (0.93), 0.97 (0.87), and 0.94 (0.76) times

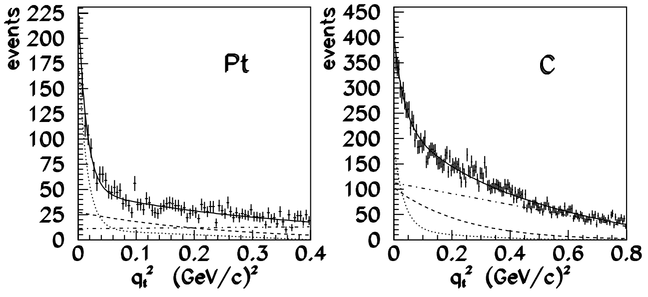

FIG. 2. q_t^2 distributions of dijets with $1.5 \leq k_t \leq 2.0$ GeV/c for the platinum and carbon targets. The lines are fits of the MC simulations to the data: coherent nuclear dissociation (dotted lines), coherent nucleon/incoherent nuclear dissociation (dashed lines), background (dash-dotted lines), and total fit (solid lines).

TABLE I. The exponent in $\sigma \propto A^{\alpha}$, experimental results for coherent dissociation and the color-transparency predictions.

k_t bin GeV/c	α	$\Delta\alpha_{\text{stat}}$	$\Delta\alpha_{\text{sys}}$	$\Delta\alpha$	α (CT)
1.25–1.5	1.64	±0.05	+0.04 −0.11	+0.06 −0.12	1.25
1.5–2.0	1.52	±0.09	±0.08	±0.12	1.45
2.0–2.5	1.55	±0.11	±0.12	±0.16	1.60

their asymptotic high-energy values for $M_J = 4.2$, 5.0, and 6.0 GeV/c^2 (masses relevant for our k_t^2 bins). We extrapolate our calculations of α to asymptotically high energies, dividing the yields by these factors. The results for each k_t bin are listed in Table I. Using more realistic wave functions, the predicted value of the asymptotic value of α is 1.45 for carbon and platinum targets. Frankfurt *et al.* [19] predict some dependence of α on k_t as well. These values, labeled α (CT), are also listed in Table I.

We have considered the sources of systematic uncertainty, which are listed in Table II. The degree to which the simulations represented correctly the effect of not including the neutral component of the jets is checked by raising the minimum total momentum of charged particles from 450 to 470 GeV/c. The difference in the final results of α with and without this requirement is taken to be the corresponding systematic uncertainty ("effect of neutrals"). The uncertainty due to using discrete masses in the Monte Carlo simulation is estimated using the difference between results, assuming that all the events in a given k_t range have one mass or another ("discrete masses"). A third uncertainty is assigned to the change in yields due to mass-distribution differences in carbon and platinum. We also observe some sensitivity to the fitting range used; the associated differences are taken as a fourth systematic uncertainty. The total systematic uncertainty is taken by adding these contributions in quadrature, retaining the signs when not symmetric.

In summary, we have measured the relative cross sections for diffractive dissociation into dijets of 500 GeV/c pions scattering from carbon and platinum targets. Extrapolating to asymptotically high energies (where $t_{\min} \longrightarrow 0$), we find that, when the cross section is parametrized as $\sigma = \sigma_0 A^{\alpha}$, $\alpha \sim 1.6$. The numerical results for the high and middle ranges of k_t are consistent with expectations based on calculations of color-transparency models. For the lower k_t range there is discrepancy, but it should be noted that this is a range where these model-dependent pQCD calculations may not be applicable [23]. The important point is that even though the results are based on data taken for only two nuclei they are far apart, and there is a very large difference between the observed A dependence and the $\sigma \propto A^{2/3}$ dependence typical of inclusive π-nucleus scattering. The clear diffractive structure of the signals and variation of the coherent cross section with A indicate that we have observed the coherent scattering of $|q\bar{q}\rangle$ pointlike configurations predicted by color-transparency.

We thank Dr. S. J. Brodsky, Dr. L. Frankfurt, Dr. G. A. Miller, and Dr. M. Strikman for many fruitful discussions. We gratefully acknowledge the staffs of Fermilab and of all the participating institutions. This research was supported by the Brazilian Conselho Nacional de Desenvolvimento Científico e Technológio, the Mexican Consejo Nacional de Ciencia y Tecnologica, the Israeli Academy of Sciences and Humanities, the United States Department of Energy, the U.S.-Israel Binational Science Foundation, and the United States National Science Foundation. Fermilab is operated by the Universities Research Association, Inc., under contract with the United States Department of Energy.

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[1] F. E. Low, Phys. Rev. D **12**, 163 (1975); S. Nussinov, Phys. Rev. Lett. **34**, 1286 (1975).

[2] A. H. Mueller, in *Proceedings of Seventeenth Rencontre de Moriond, Les Arcs, 1982,* edited by J Tran Thanh Van (Editions Frontieres, Gif-sur-Yvette, 1982), Vol. I, p. 13; S. J. Brodsky, in *Proceedings of the Thirteenth International Symposium on Multiparticle Dynamics,* edited by W. Kittel, W. Metzger, and A. Stergiou (World Scientific, Singapore, 1982), p. 963.

[3] G. R. Farrar, H. Liu, L. L. Frankfurt, and M. I. Strikman, Phys. Rev. Lett. **61**, 686 (1988).

[4] B. K. Jennings and G. A. Miller, Phys. Lett. B **236**, 209 (1990); B. K. Jennings and G. A. Miller, Phys. Rev. D **44**, 692 (1991); Phys. Rev. Lett. **69**, 3619 (1992); Phys. Lett. B **274**, 442 (1992).

[5] S. J. Brodsky and A. H. Mueller, Phys. Lett. B **206**, 685 (1988).

[6] L. Frankfurt, G. A. Miller, and M. Strikman, Comments Nucl. Part. Phys. **21**, 1 (1992); Nucl. Phys. **A555**, 752 (1993).

[7] L. Frankurt and M. Strikman, Phys. Rep. **160**, 235 (1988).

[8] H.-N. Li and G. Sterman, Nucl. Phys. **B381**, 129 (1992); J. Botts and G. Sterman, Nucl. Phys. **B325**, 62 (1989).

[9] I. Mardor *et al.,* Phys. Rev. Lett. **81**, 5085 (1998).

[10] N. C. R. Makins *et al.,* Phys. Rev. Lett. **72**, 1986 (1994); T. G. O'Neill *et al.,* Phys. Lett. B **351**, 87 (1995).

TABLE II. The systematic errors in the parameter α.

k_t bin GeV/c	Effect of neutrals	Discreet masses	Different efficiency for C and Pt	Fit range sensitivity	Total
1.25–1.5	−0.09	+0.03 −0.06	±0.02	±0.02	+0.04 −0.11
1.5–2.0	±0.03	±0.03	±0.06	±0.04	±0.08
2.0–2.5	±0.06	±0.05	±0.06	±0.07	±0.12

[11] D. Abbott *et al.,* Phys. Rev. Lett. **80**, 5072 (1998).

[12] M.D. Sokoloff *et al.,* Phys. Rev. Lett. **57**, 3003 (1986).

[13] M.R. Adams *et al.,* Z. Phys. C **74**, 237 (1997).

[14] M.R. Adams *et al.,* Phys. Rev. Lett. **74**, 1525 (1995).

[15] H. Abramowicz and A. Caldwell, Rev. Mod. Phys. **71**, 1275 (1999).

[16] S.J. Brodsky and G.R. Farrar, Phys. Rev. Lett. **31**, 1153 (1973).

[17] G. Sterman and P. Stoler, Annu. Rev. Nucl. Part. Sci. **43**, 193 (1997), and references therein.

[18] G. Bertsch, S.J. Brodsky, A.S. Goldhaber, and J. Gunion, Phys. Rev. Lett. **47**, 297 (1981).

[19] L.L. Frankfurt, G.A. Miller, and M. Strikman, Phys. Lett. B **304**, 1 (1993).

[20] L.L. Frankfurt, G.A. Miller, and M. Strikman, Found. Phys. **30**, 533 (2000); L.L. Frankfurt, G.A. Miller, and M. Strikman, Report No. NT@UW-99-25.

[21] E791 Collaboration, E.M. Aitala *et al.,* Eur. Phys. J. C **4**, 1 (1999), and references therein.

[22] JADE Collaboration, W. Bartel *et al.,* Z. Phys. C **33**, 23 (1986).

[23] E791 Collaboration, E.M. Aitala *et al.,* preceding Letter, Phys. Rev. Lett. **86**, 4768 (2001).

[24] C.W. de Jager, H. de Vries, and C. de Vries, At. Data Nucl. Data Tables **14**, 479 (1974); the radius for Pt is derived from that reported for Au scaled by $A^{1/3}$.

[25] H.-U. Bengtsson and T. Sjöstrand, Comput. Phys. Commun. **82**, 74 (1994); T. Sjöstrand, PYTHIA 5.7 and JETSET 7.4, Report No. CERN-TH.7112/93, 1995.

[26] G.P. Lepage and S.J. Brodsky, Phys. Rev. D **22**, 2157 (1980); S.J. Brodsky and G.P. Lepage, Phys. Scr. **23**, 945 (1981); S.J. Brodsky, Springer Tracts Mod. Phys. **100**, 81 (1982).

[27] A.V. Efremov and A.V. Radyushkin, Theor. Math. Phys. **42**, 97 (1980).