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Diffraction Dissociation of High-Energy Protons on Hydrogen and Deuterium Targets

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We report results from a measurement of the inclusive processes $pp \to Xp$ and $pd \to Xd$ in the range $5 < M_x^2/s < 0.1$, $0.01 \lesssim |t| \lesssim 0.1$ $(\text{GeV}/c)^2$, and incident proton momenta of 65, 154, and 372 GeV/c. Both pp and pd data show an exponential t dependence and a dominant $1/M_x^2$ behavior for $M_x^2/s \lesssim 0.05$. By comparing pp and pd data we test factorization and, using the Glauber model, we measure the XN total cross section, $\sigma_{XN} = 43 \pm 10$ mb.

In an experiment designed to study inelastic, high-energy diffractive phenomena, we have obtained the invariant differential cross sections $d^2\sigma/dt\,d(M_x^2/s)$ for the inclusive reactions

$$pp \to Xp \tag{1}$$

and

$$pd \to Xd \tag{2}$$

by measuring the energy and angle of low-energy recoil protons and deuterons from a gas jet target situated in the main ring of the Fermi National Accelerator Laboratory. We report results for three values of incident momentum p_0 (65, 154, and 372 GeV/c) over an invariant-mass range of the unobserved system $5s < M_x^2 < 0.1s$ and and for small values of the square of the invariant-four-momentum transfer, $0.01 \lesssim |t| \lesssim 0.06$ $(\text{GeV}/c)^2$ for $pp \to Xp$ and $0.025 \lesssim |t| \lesssim 0.17$ (GeV $/c)^2$ for $pd \to Xd$.

At small momentum transfer of this experiment, the target particle (p or d) is expected to recoil coherently. The high incident energy allows the incoming proton to dissociate into high-mass states while keeping the minimum momentum transfer $|t_{\min}|^{1/2} \simeq M_x^2/2p_{\text{lab}}$ within the coherence region. We may then test whether the cross sections for Reactions (1) and (2) scale to their respective elastic cross sections, according to the concept of factorization at the inelastic vertex. Moreover, by applying the Glauber model[1,2] we can deduce the total cross section, σ_{XN}, of the diffractive state with mass M_x and the quantum numbers of the proton interacting with a single nucleon.

For these reactions, the square of the missing mass is given quite accurately by

$$\frac{M_x^2 - m_p^2}{s} \simeq 1 - x \simeq \frac{|t|^{1/2}}{m_r}\left(\cos\theta - \frac{p_0 + m_r}{p_0}\frac{|t|^{1/2}}{2m_r}\right), \tag{3}$$

where x is the Feynman scaling variable defined as $p_\parallel/p_{\max}$ in the center-of-mass system, θ is the scattering angle of the recoil target particle relative to the incident proton direction, m_r is the mass of the recoil particle, and $s \simeq 2m_r p_0$ is the square of the total center-of-mass energy. The experimental arrangement[3] was similar to that described Akimov *et al.*[4] The recoil protons or deuterons were detected and their kinetic energy T, hence $|t|=2m_rT$, was measured by stacks of surface-barrier solid-state detectors mounted on a movable carriage placed 1.5 m away from the jet target inside an extension of the main accelerator's vacuum system. Each stack consisted of three detectors, 0.15, 1.5, and 5.0 mm in thickness, and 0.25 cm^2 in area, sandwiched together with suitable collimators. Only recoils which stopped in either the second or the third detector were used for the cross-section determination. The resolution in the measurement of the missing mass was $\delta M_x^2 \simeq 10^{-3}p_0$, determined largely by the ± 2.5-mrad angular resolution due to the ± 3 mm width of the gas jet target and the size of the detectors.

A special feature of this experiment, designed for measuring the background, was the use of a tungsten cylinder, 1.2 cm in diameter and 4 cm long, placed on a movable mount close to the target. This "antislit" could be remotely positioned to occlude direct rays from the target region to any chosen detector stack. With the antislit in position, any counts in the shadowed stack had to originate from background sources such as gas outside the target region or rescattering from the walls of the vacuum chamber of elastically scattered target particles. The data were corrected for this background measured periodically throughout the experiment. The correction in $d\sigma/dx$ was flat in x and ranged from 2 to 20% for the pd measurements and from 8 to 30% for the pp measurements. A conservative 15% error was assigned to this correction consistent with the statistical accuracy and the systematic run-to-run variations of the background measurements.

The cross sections were normalized using a detector stack situated at a fixed recoil angle which detected recoils from small-angle elastic scattering. The differential cross sections for these elastic reactions were measured previously[4,5] and we have used the results of those measurements for the determination of the absolute value of the invariant cross sections reported here. Our normalization procedure was the same as that described by Akimov *et al.*[6] and Bartenev *et al.*[7] The error in the ratio of the inelastic to the elastic cross sections as well as the relative energy to energy normalization errors are quite small, typically about ± 2%. The major error in the absolute normalization of the cross sections arises from the extrapolation of the elastic cross sections to the optical point.[8] We estimate this error to be about ± 10% for the pd data and about ± 5% for the pp data.

The t distributions of the pp data are fitted adequately by a simple exponential function e^{bt}, with an average slope parameter b of 7 ± 1 $(\text{GeV}/c)^{-2}$. The uncertainty is largely systematic. No significant turnover at small $|t|$ values is evident, contrary to some theoretical suggestions.[9] The pd distributions are strongly damped as $|t|$ increases, reflecting the extended size of the deuteron.

In order to study the x dependence of the cross sections, we have fitted the data around the average t values covered by the detectors using the form

$$\frac{d^2\sigma}{dt\,dx}=\left[\frac{d^2\sigma}{dt\,dx}\right]_{t=t_0}\frac{S^2(t/4)e^{bt}}{S^2(t_0/4)e^{bt_0}}, \tag{4}$$

where $S(t)$ is the deuteron form factor[4] in the pd case, and equal to 1 in the pp case. In this way we have determined $d^2\sigma/dt\,dx$ as a function of x with high statistical precision at two t values, $|t_0|=0.015$ and 0.05 $(\text{GeV}/c)^2$ for pp and $|t_0|=0.035$ and 0.13 $(\text{GeV}/c)^2$ for pd. The numerical values of the cross sections obtained in this manner are tabulated in Table I. The slope parameter b is not tabulated for each t_0 because of the large uncertainties due to the restricted t range.

Our results exhibit a small energy dependence and a dominant $1/(1-x)$ behavior for $1-x \lesssim 0.05$. This behavior is evident in Figs. 1(a) and 1(b), where we have plotted $(1-x)d^2\sigma/dt\,dx$ as a function of $1-x$. Figure 1(a) includes pd results from Ref. 6 and Fig. 1(b) includes pp results from Childress *et al.*[10] The two sets of pd data agree very well. The two sets of pp data are in general agreement except that the data of Childress *et al.* lie systematically below ours in the region $0.01 < 1-x < 0.02$. The normalization and shape of our pp cross sections at $|t|=0.05$ $(\text{GeV}/c)^2$ and $p_0=154$ GeV/c agree to within 5% with the empirical fit to pp inclusive data reported by Anderson *et al.*[11]:

$$d^2\sigma/dt\,dx = A_1(s,t)/(1-x) + A_2(s,t)(1-x). \tag{5}$$

We find that our cross sections are described very well by this form, with A_1 decreasing slowly with increasing s and A_2 constant.

The pp and pd data are compared directly in Fig. 1(c), where we plot the ratio $dN/dx=(d^2\sigma/dt\,dx)/(d\sigma_{el}/dt)$ vs $(1-x)$ at $|t|=0.05$ and at dif-

TABLE I. Cross sections $d^2\sigma/dt\,dx$ [mb $(\text{GeV}/c)^{-2}$] as a function of $(1-x)$.

Channel $\lvert t\rvert(\text{GeV}/c)^2$	1-x	65 GeV/c	154 GeV/c	372 GeV/c
pp → Xp	0.0074			531.1 ± 18.2
$\lvert t\rvert$ = 0.015	0.0120			309.5 ± 12.5
	0.0160		250.4 ± 11.9	232.5 ± 11.3
	0.0200		210.6 ± 10.4	184.8 ± 9.5
	0.0240		183.9 ± 8.9	168.9 ± 8.2
	0.0300		166.6 ± 9.4	139.6 ± 9.4
	0.0350		160.4 ± 8.1	141.7 ± 8.9
	0.0400	166.5 ± 9.0	140.5 ± 8.2	126.1 ± 9.0
	0.0450	147.0 ± 8.3	137.6 ± 7.2	123.4 ± 7.7
	0.0500	139.8 ± 8.7	130.0 ± 7.7	119.1 ± 7.9
	0.0550	136.6 ± 9.1	122.4 ± 7.9	122.4 ± 8.1
	0.0620	124.5 ± 8.7	107.6 ± 7.3	103.2 ± 7.6
pp → Xp	0.0110			291.7 ± 12.4
$\lvert t\rvert$ = 0.05	0.0170		220.1 ± 12.2	170.4 ± 11.6
	0.0250		154.1 ± 6.2	122.9 ± 6.9
	0.0330		123.1 ± 6.5	98.5 ± 7.8
	0.0500	108.2 ± 5.9	92.4 ± 5.4	81.3 ± 6.1
	0.0550	107.1 ± 5.7	93.7 ± 5.4	81.3 ± 5.9
	0.0620	95.7 ± 5.8	81.7 ± 5.2	77.9 ± 5.8
	0.0700	93.4 ± 5.0	80.4 ± 4.5	74.0 ± 4.8
	0.0800	87.8 ± 4.7	82.2 ± 4.4	76.0 ± 4.3
	0.0900	89.4 ± 4.7	79.0 ± 4.4	80.5 ± 4.2
	0.1000	87.5 ± 5.5	80.6 ± 4.6	74.0 ± 4.0
pd → Xd	0.0070			530.4 ± 13.4
$\lvert t\rvert$ = 0.035	0.0100		441.0 ± 11.2	385.3 ± 10.2
	0.0115		383.5 ± 10.8	325.9 ± 9.8
	0.0130		348.3 ± 13.6	307.9 ± 12.8
	0.0145		331.1 ± 11.8	271.3 ± 10.6
	0.0160		291.1 ± 9.6	265.5 ± 8.8
	0.0175		273.5 ± 9.4	230.9 ± 8.4
	0.0200	280.0 ± 8.8	235.5 ± 7.2	224.3 ± 7.0
	0.0225	253.5 ± 8.6	225.5 ± 8.4	197.3 ± 8.4
	0.0250	224.9 ± 8.6	202.1 ± 6.6	192.1 ± 6.0
	0.0275	200.5 ± 8.6	195.1 ± 7.8	182.9 ± 7.4
	0.0310	203.1 ± 6.8	165.7 ± 5.8	152.1 ± 5.6
	0.0350	192.5 ± 6.0	166.1 ± 5.6	153.1 ± 5.4
	0.0400	169.5 ± 5.2	152.9 ± 4.6	146.1 ± 4.4
	0.0450	161.7 ± 4.8	147.3 ± 4.2	137.1 ± 4.0
	0.0500	154.3 ± 4.8	143.5 ± 4.4	132.8 ± 4.2
	0.0600	155.3 ± 6.8	137.1 ± 5.6	128.6 ± 5.4
pd → Xd	0.0045			77.6 ± 3.6
$\lvert t\rvert$ = 0.13	0.0060			65.4 ± 3.1
	0.0115		39.2 ± 1.2	33.7 ± 1.1
	0.0180		24.8 ± 1.2	25.0 ± 1.2
	0.0250	24.6 ± 1.1	19.7 ± 0.9	19.5 ± 0.9
	0.0325	21.6 ± 1.0	19.0 ± 0.9	18.0 ± 0.9
	0.0400	17.9 ± 0.9	15.7 ± 0.8	15.8 ± 0.8
	0.0500	17.3 ± 1.2	17.2 ± 1.2	12.7 ± 1.1
	0.0600	16.7 ± 0.8	13.9 ± 0.7	14.0 ± 0.7
	0.0700	14.6 ± 0.7	14.7 ± 0.6	12.8 ± 0.6
	0.0800	15.2 ± 0.8	15.7 ± 0.6	14.1 ± 0.6
	0.0950	15.4 ± 1.0	16.2 ± 0.8	15.1 ± 0.8

ferent lab momenta but approximately equal s values. We note that the two sets of data approach each other as $1-x$ decreases, a behavior expected from factorization. In a picture with a factorizable Pomeron exchange that dominates both the elastic cross section and the diffractive cross section at small $1-x$, where the A_1 term in Eq. (5) is most important, the ratio of diffractive to elastic cross section should be independent of target-particle type. At higher values of $1-x$ additional exchanges spoil this simple factorization rule. To obtain a quantitative test of factorization we fit dN/dx to the form of Eq. (5). We find that, while $A_2^{pd} \sim 2A_2^{pp}$, A_1^{pd} is equal to A_1^{pp} to within the 5% experimental uncertainty, in excellent agreement with the picture of a dominant

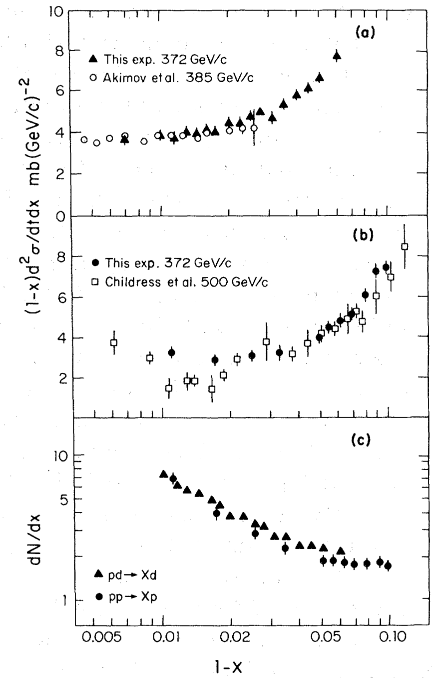

FIG. 1. (a) $(1-x)d^2\sigma/dt\,dx$ vs $1-x$ for $pd \to Xd$ at $\lvert t\rvert = 0.035$ $(\text{GeV}/c)^2$. (b) The same for $pp \to Xp$ at $\lvert t\rvert = 0.05$ $(\text{GeV}/c)^2$. (c) $dN/dx = (d^2\sigma/dt\,dx)/(d\sigma_{el}/dt)$ at $\lvert t\rvert = 0.05$ $(\text{GeV}/c)^2$ for $pd \to Xd$ at 154 GeV/c and for $pp \to Xp$ at 372 GeV/c (approximately same s value).

factorizable Pomeron at low values of $1-x$.

The data can be further understood in the framework of the well-known triple-Regge model[12] (TR), where the strong $1/(1-x)$ behavior reflects the dominance of the triple-Pomeron coupling, G_{PPP}, for which we obtain $G_{PPP} = 3.45 \pm 0.17$ mb $(\text{GeV}/c)^{-2}$, in good agreement with previous determinations.[13]

We now treat the deuteron as a composite particle and compare pp and pd data at the same incident lab momentum p_0. For this purpose, we plot in Fig. 2 the ratio

$$R = \left[\frac{d^2\sigma/dt\,dx}{d\sigma_{el}/dt}\right]_{pp}\left\{\left[\frac{d^2\sigma/dt\,dx}{d\sigma_{el}/dt}\right]_{pd}\right\}^{-1}, \qquad (6)$$

where the values of $1-x$ for pd are now twice as large as those shown in Table I because of the change in the definition of s to $s \simeq 2m_p p_0$. Using the Glauber model, we write[1,2]

$$\frac{d\sigma_{el}^{pp}}{dt} = \frac{1}{4S^2(t/4)}\frac{d\sigma_{el}^{pd}}{dt}[1+\Delta_{el}(t)],$$
$$\frac{d^2\sigma^{pp}}{dt\,dx} = \frac{1}{4S^2(t/4)}\frac{d^2\sigma^{pd}}{dt\,dx}[1+\Delta_{in}(t)] + \Pi. \qquad (7)$$

Here $S(t)$ is the deuteron form factor, Δ_{el} and

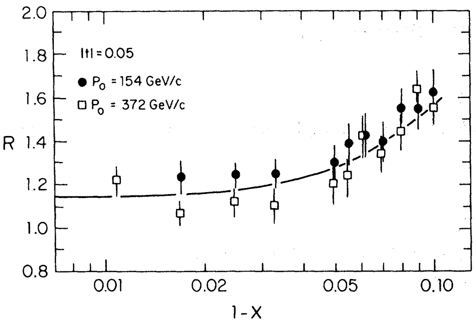

FIG. 2. The ratio

$$R=\left[\frac{d^2\sigma/dt\,dx}{d\sigma_{el}/dt}\right]_{pp}\left\{\left[\frac{d^2\sigma/dt\,dx}{d\sigma_{el}/dt}\right]_{pd}\right\}^{-1}$$

vs $1-x$ for $p_0=154$ and 372 GeV/c. The curve is obtained from an evaluation of Eq. (8).

Δ_{in} are the elastic and inelastic double-scattering corrections, and Π stands for the contribution of pion exchanges which are forbidden in coherent pd reactions but may be present in the pp interactions. Other $I=1$ exchanges such as ρ or A_2 which may also contribute to the pp inelastic cross sections are neglected along with the contribution of $I=1$ exchanges to the elastic cross sections. The ratio R can now be written as follows:

$$R\cong 1+\Delta_{in}(t)-\Delta_{el}(t)+\Pi\frac{d\sigma_{el}^{pd}}{dt}\left(\frac{d\sigma_{el}^{pp}}{dt}\frac{d^2\sigma^{pd}}{dt\,dx}\right)^{-1}. \quad (8)$$

In the region $1-x<0.05$, where the contribution from pion exchange is small, R is approximately independent of $1-x$, corresponding to $\Delta_{in}-\Delta_{el}\sim 0.20$ at 154 GeV/c and ~ 0.10 at 372 GeV/c. While this suggests that $\Delta_{in}-\Delta_{el}$ decreases with increasing energy, the data are consistent with an energy-independent $\Delta_{in}-\Delta_{el}$.

For $1-x>0.05$ the contribution of the pion-exchange amplitude to the pp cross section becomes important. The evaluation of Eq. (8), using $\Delta_{in}-\Delta_{el}=0.14$ and Bishari's[14] pion-exchange estimate, is shown by the curve in Fig. 2 to be in good agreement with the data. Thus, the ratio of the pp to pd inelastic cross sections at 154 and 372 GeV/c can be understood as the combined effect of Glauber corrections to the pd cross sections and pion-exchange contributions to the pp cross sections.

In a simple Glauber picture[4] $\Delta_{el}\sim 0.13$; thus $\Delta_{in}\sim 2\Delta_{el}$. Moreover, since[2] $\Delta_{in}\approx\Delta_{el}[1+(\sigma_{XN}/\sigma_{NN})]$, where σ_{XN} is the total cross section of the M_x^2 system on a nucleon, we obtain $\sigma_{XN}=43\pm 10$ mb, a value remarkably close to σ_{NN}, and significantly smaller than expected from a cascading multiparticle state.[15]

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