Inclusive $pd \to pX$ and $pn \to pX$ Cross Sections between 50 and 400 GeV*

B. Robinson,† K. Abe, J. Carr, J. Keyne, A. Pagnamenta, F. Sannes, I. Siotis, and R. Stanek

Rutgers University, New Brunswick, New Jersey 08903, and Imperial College, London SW7, United Kingdom, and University of Illinois, Chicago, Illinois 60680

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We have measured inclusive cross sections for the reaction $pd \to pX$ in the region $0.15 < |t| < 0.39$ GeV^2, $100 < s < 750$ GeV^2 and $0.80 < x < 0.92$ using the acceleration ramp and deuterium-gas jet target at Fermilab. These measurements are combined with our earlier measurements of $pp \to pX$ to obtain inclusive cross sections for $pn \to pX$.

In a recent experiment we have measured the inclusive cross sections for the reactions

$$pp \to pX \; (1+2 \to 3+X), \tag{1}$$

$$pd \to pX \; (1+2 \to 3+X), \tag{2}$$

using the hydrogen- and deuterium-gas jet targets in the Fermilab main ring. The results of the $pp \to pX$ measurements were reported earlier.[1] In this Letter we present cross sections for the reaction $pd \to pX$ and combine the two sets of measurements to obtain invariant cross sections for the reaction

$$pn \to pX \; (1+2 \to 3+X). \tag{3}$$

Since we wish to compare pd data to pp data, it is convenient to use the nucleon rather than the deuteron mass in defining the kinematic variables of Reaction (2); i.e., we assume independent nucleon-nucleon interactions, the second nucleon in the deuteron being a spectator. In order to take into account the smearing of the kinematic variables due to Fermi motion we use the average values defined by

$$\langle s \rangle = s + E_1 \langle p_F{}^2 \rangle / m_2, \tag{4}$$

$$\langle t \rangle = t - E_3 \langle p_F{}^2 \rangle / m_2, \tag{5}$$

$$\langle x \rangle = x - \langle p_F{}^2 \rangle / 2m_2{}^2, \tag{6}$$

where m_2 is the nucleon mass; $x \equiv 1 - M_X{}^2/s$; s, t, and $M_X{}^2$ are the squares of the total center-of-mass energy, the four-momentum transfer, and the mass of X, respectively, for a target nucleon at rest; and $\langle p_F{}^2 \rangle = 0.012$ GeV^2 is the mean square of the nucleon momentum in the deuteron due to Fermi motion. For the kinematic region of this experiment we have $\langle s \rangle / s \simeq 1.006$, $\langle t \rangle - t \simeq -0.013$ GeV^2, and $\langle x \rangle - x \simeq -0.007$.

The recoil particles were detected and identified as protons in a spectrometer consisting of a series of scintillation counters as described in Ref. 1. In addition, we detected elastically scattered deuterons in a small solid-state detector at 85.5° from the beam direction. The beam-target luminosity was determined as in Ref. 1 by use of the pd elastic differential cross sections of Akimov *et al.*[2] and the total pd cross sections of Carroll *et al.*[3]

The $pd \to pX$ data are shown in Fig. 1. Only sta-

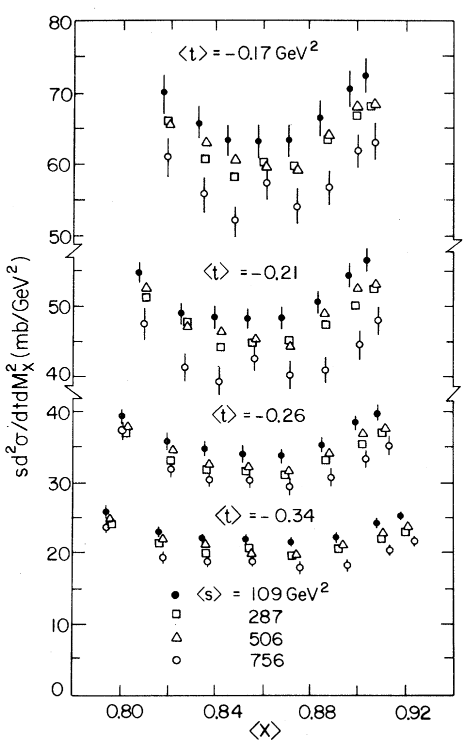

FIG. 1. Inclusive cross sections for the reaction $pd \to pX$. The variables $\langle s \rangle$, $\langle t \rangle$, and $\langle x \rangle$ are defined as if the target consisted of protons and neutrons with Fermi motion rather than deuterons [see text and Eqs. (4)–(6)]. Errors for the two intermediate energies are similar to those shown for the extreme energies.

tistical errors to which we have added quadratically systematic errors of ±3% are displayed. The uncertainty in the overall normalization is ±15% as for our earlier measurements[1] of $pp \to pX$. However, since both reactions were studied with the same apparatus, the only difference being the gas used in the jet target, we estimate the relative error between the pp and pd data to be only ±4%, due solely to uncertainties in the pp and pd elastic cross sections.

The cross sections for $pd \to pX$ look very similar to those for $pp \to pX$.[1] They show a weak s dependence and an exponential t dependence of $\sim e^{6t}$. There is a minimum in the x distribution at $x = 0.87$ and the absolute value of the $pd \to pX$ cross section is about twice that of $pp \to pX$. However, it should not be assumed from this similarity that the cross sections for $pn \to pX$ are the same as for $pp \to pX$. The measured shapes of the pd inclusive spectra in our kinematic region (x near 1, low $|t|$) are determined to a large extent by the Fermi motion of the target nucleons as well as the rescattering of the recoil particle off the spectator nucleon in the deuteron.

To extract the $pn \to pX$ spectra we assume the impulse approximation. In this approximation the proton and neutron in the deuteron are considered as independent particles in close proximity. The closeness of the nucleons gives rise to a shadowing of one by the other, effectively lowering the luminosity of both relative to an equal number of free particles. We assume that the decrease in luminosity for inclusive reactions is the same as that for total cross sections, i.e., $\sigma_{pd} = \sigma_{pp} + \sigma_{pn} - \delta$, where $\delta = \sigma_{pn}\sigma_{pp}/4\pi\langle r^2\rangle$ with $\langle r^2\rangle = 31$ mb. This is the cross-section deficit of Glauber theory[4] and amounts to a decrease of ~5% in the effective pd cross section over our energy range.

The effect of the deuteron potential in the impulse approximation is to give the nucleons a center-of-mass momentum or Fermi motion. As a result of this our spectrometer will detect recoil protons originating from elastic scattering off the moving target proton. To estimate this effect we use the Hulthén wave function[5] and measured pp elastic scattering cross sections[6] in a Monte Carlo program to simulate the pp elastic spectra as seen by our spectrometer. These spectra are approximately Gaussian centered around $x = 1 - M_p^2/s$. The same Monte Carlo program is used to smear the inelastic $pp \to pX$ spectra for which we use a composite input of all available data[7-9] in addition to our published measurements.[1]

For both the pp elastic and inelastic cross sections mentioned above we use the forms for "free" protons but modified by the deuteron form factor[4] $s(t)$ in order to exclude interactions which result in a deuteron which is not detected in the final state, i.e., for the pp differential cross sections we use $(d\sigma/dt_{\text{free}})[1 - s^2(t)]$.

An additional feature of the Monte Carlo program is the inclusion of an estimate of the rescattering of the recoil protons by the spectator neutron which has the effect of spreading the x distributions for those protons which interact. For this we assume that the neutron on average sits at an rms radius of $(31\ \text{mb})^{1/2}$ and that the reaction is the same as for free np scattering. The probability for an interaction was taken to be simply $\sigma_{pn}/4\pi\langle r^2\rangle$ and the scattering angle was weighted by low-energy np differential-cross-section measurements.[10]

In summary, our final $pn \to pX$ cross sections were obtained in the following manner: (1) Our $pd \to pX$ cross sections were multiplied by 1.05 to correct for the shadowing effect. (2) From the resulting cross sections we subtracted the $pp \to pp$ elastic and $pp \to pX$ inclusive cross sections both of which were Fermi smeared, corrected for coherent pd scattering (by including the deuteron form factor), and corrected for rescattering off the spectator neutron. A typical spectrum and the distributions from which it was derived are shown in Fig. 2.

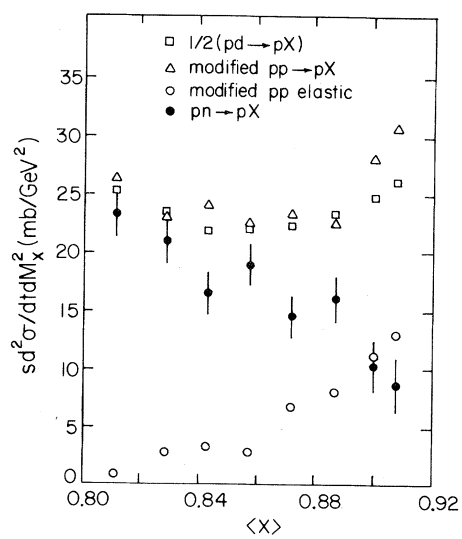

FIG. 2. Sample extraction of $pn \to pX$ cross sections from $pd \to pX$, $pp \to pX$, and $pp \to pp$ cross sections at $\langle s\rangle = 287\ \text{GeV}^2$ and $\langle t\rangle = -0.21\ \text{GeV}^2$.

The final $pn \to pX$ spectra are plotted in Fig. 3. They contain the effects of Fermi motion and rescattering which have not been unfolded. The normalization errors have been calculated by taking into account the fact that the absolute uncertainties in the $pp \to pX$ and $pd \to pX$ data are correlated as a result of the use of the same apparatus for both measurements. This leads to overall normalization uncertainties for the $pn \to pX$ data of ± 5.6, ± 4.0, ± 2.9, and ± 1.8 mb/GeV^2 at $\langle -t \rangle = 0.17$, 0.21, 0.26, and 0.34 GeV^2, respectively.

As can be seen from Fig. 3, the invariant cross section for $pn \to pX$ falls as x tends to 1 in contrast to that for $pp \to pX$ which rises above $x = 0.88$. Also, at fixed x and t the $pn \to pX$ data show no significant energy dependence although a 20% drop between the two extreme energies is possible within errors.

The study of the charge-exchange reaction $pn \to pX$ (or equivalently $pp \to nX$)[11] near $x=1$ provides valuable information on the nondiffractive component of the reaction $pp \to pX$. The most popular phenomenological framework for discussing both reactions in our kinematic region has been the triple-Regge (TR) formalism[11] which leads to a prediction for the invariant cross section for particle 3 in Reactions (1) and (3) of

$$\frac{s\,d^2\sigma}{dt\,dM_X^2} = \frac{s_0}{s} \sum_{ijk} G_{ijk}(t) \left(\frac{s}{M_X^2}\right)^{\alpha_i(t)+\alpha_j(t)} \left(\frac{M_X^2}{s_0}\right)^{\alpha_k(0)}, \tag{7}$$

where $s_0 = 1$ GeV^2 and the G_{ijk} are the TR couplings.[12]

It was first suggested by Bishari[13] that pion exchange might be the dominant mechanism for the charge-exchange reaction (3). By extrapolating to the pion pole, Field and Fox[11] estimate the contribution of the $\pi\pi P$ and $\pi\pi R$ terms to the process $pn \to pX$. They obtain

$$G_{\pi\pi k}(t) = \frac{1}{4\pi} \frac{g_{\pi np}^{\ 2}}{4\pi} \sigma_t^{\,k}(\pi p) \frac{(-t)e^{b(t-\mu^2)}}{(t-\mu^2)^2} \tag{8}$$

for the TR couplings, where k represents Pomeron or Reggeon exchange and $\mu^2 = m_\pi^{\ 2}$. The total πp cross section is taken to be $\sigma_t(\pi p) = \sigma_t^{\,P}(\pi p) + \sigma_t^{\,R}(\pi p)/\sqrt{s}$ with $\sigma_t^{\,P}(\pi p) = 21$ mb and $\sigma_t^{\,R}(\pi p) = 20$ mb and the on-mass-shell coupling $g_{\pi np}^{\ 2}/4\pi = 2g_{\pi pp}^{\ 2}/4\pi$ is 30. For simplicity we neglect any off-shell corrections by putting $b=0$ in Eq. (8) and in the TR formula (7) we use $\alpha_\pi(t) = 0.0 + t$, $\alpha_P(0) = 1$, and $\alpha_R(0) = 0.5$. Furthermore, in order to compare with the data, we modify the theoretical prediction by a Monte Carlo program to account for Fermi motion and rescattering. The results, which are shown in Fig. 3 for $\langle s \rangle = 506$ GeV^2 and $\langle t \rangle = -0.17$ and -0.34 GeV^2, are in reasonable agreement with the data. If we allow for off-shell corrections by taking $b > 0$ in Eq. (8), the $\pi\pi P$ and $\pi\pi R$ terms alone give too low a cross section and an extra RRP term is needed in the TR formula (7) to make up the difference. Although the accuracy of our $pn \to pX$ cross sections is insufficient to allow us to determine b uniquely, the general features of the data support the hypothesis that pion exchange plays an important role in the charge-exchange reaction $pn \to pX$. The $\pi\pi P$ and $\pi\pi R$ terms should therefore be included in any analysis of the reaction $pp \to pX$ which otherwise will overestimate the other TR

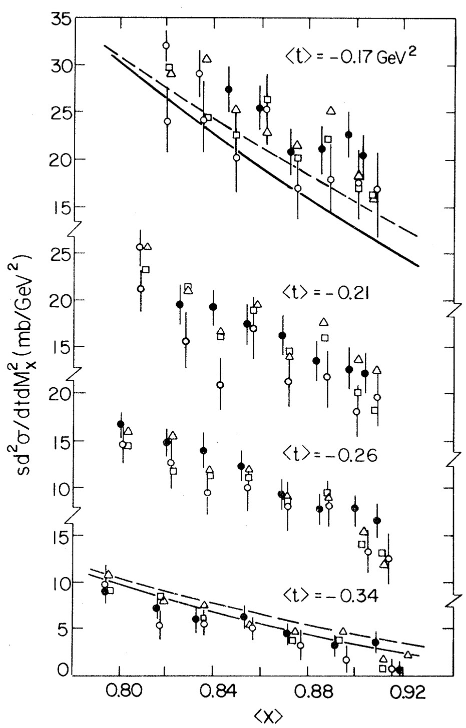

FIG. 3. Inclusive cross sections for the reaction $pn \to pX$. The symbols representing $\langle s \rangle = 109$, 287, 506, and 756 GeV^2 are as defined in Fig. 1. The solid curves are the sum of the $\pi\pi P$ and $\pi\pi R$ contributions to the TR formula (7) with couplings given by Eq. (8). These theoretical curves have been modified, resulting in the dashed curves, to account for Fermi motion and rescattering effects which have not been unfolded from the data.

contributions, mainly the *RRP* term.

Finally, at high energy and large M_X^2 the cross sections for the reaction $pn \to pX$ are expected to be similar to those for $pp \to nX$, assuming the dominant mechanism to be pion exchange, since $\sigma_t(\pi^+p) \simeq \sigma_t(\pi^-p)$. We therefore find it difficult to reconcile the cross sections reported in this Letter with those of a recent intersecting-storage-ring experiment[14] for the reaction $pp \to nX$ which are a factor 3 or more lower in the kinematic region where the two experiments overlap.

We wish to thank the members of the Fermilab Internal Target Laboratory and the Accelerator Section for their help and cooperation.

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†Present address: University of Washington, Seattle, Wash. 98105.

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COMMENTS

Comment: What Can We Learn from Three-Body Reactions?*

D. D. Brayshaw†‡

Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachussets 02139

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It is pointed out that serious flaws in the models considered by Haftel and Petersen in their recent Letter preclude both a comparison with previous work by this author, and any direct relevance to N-d scattering experiments.

Ever since exact three-body calculations became feasible, theorists have attempted to use the three-nucleon system as a probe of the unknown (off-shell) characteristics of the nuclear force, which is a laudable objective. However, the $3N$ system does not exist in isolation, and this approach is only valuable when applied to models which really *could* represent the N-N interaction (allowing for the limitations of a purely nonrelativistic treatment). In particular, there is simply no point in attempting to draw significant conclusions from models which violate certain general principles.

In a recent Letter, Haftel and Petersen[1] suggested that sizable off-shell effects might be observed in n-d breakup. Unfortunately, their mod-