

Excitation of High-Energy Protons into Low-Mass States in  $p$ - $d$  Interactions\*

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(Received 1 May 1975)

We have measured  $p$ - $d$  inelastic scattering at small momentum transfer by detecting the slow-recoil deuterons from a deuterium-gas-jet target. The coherent diffraction dissociation of protons on deuterons was studied in the region  $0.03 < |t| < 0.07$  (GeV/c)<sup>2</sup>,  $1.4 < M_X^2 < 4$  GeV<sup>2</sup>, and for energies from 50 to 275 GeV. In this region, the diffractive cross section exhibits structure and is dominated by an enhancement at  $M_X^2 \sim 1.9$  GeV<sup>2</sup>.

In an experiment performed at the Fermi National Accelerator Laboratory we studied the coherent inclusive reaction

$$p + d \rightarrow X + d, \quad (1)$$

at small momentum transfer.<sup>1</sup> Here we report results in the range  $m_p^2 < M_X^2 < 4$  GeV<sup>2</sup> which covers several of the known resonant states of the proton. Data were obtained at incident energies of 50, 180, and 275 GeV. Excitation to states of higher mass is reported in the following Letter.<sup>2</sup>

The target consisted of a deuterium gas jet<sup>3</sup> placed in the internal beam of the accelerator. The slow-recoil deuterons were detected by stacks of two silicon solid-state detectors (surface barrier) of thickness typically 200  $\mu$ m for the front and 1500  $\mu$ m for the rear detector. Only recoils stopping in the rear detector were accepted, and deuterons were unambiguously identified by the energy deposited in each detector. This technique limits the four-momentum transfer that could be measured to the range<sup>4</sup>  $0.03 \leq |t| \leq 0.07$  (GeV/c)<sup>2</sup>. The detectors were mounted near 90° with respect to the beam direction on a movable carriage at a distance of 2.5 m from the target and each stack subtended a solid angle  $\Delta\Omega \sim 16 \times 10^{-6}$  sr.

The detection technique of slow recoils from high-energy collisions has been previously used for the measurement of  $p$ - $p$  elastic<sup>5</sup> and inelastic<sup>6</sup> scattering as well as for  $p$ - $d$  elastic scattering.<sup>7</sup> A description of the apparatus and method is given elsewhere<sup>8</sup> along with a discussion of the measurement of elastic  $p$ - $d$  scattering by the authors of this Letter.

At a fixed recoil angle  $\omega$  (measured from 90°) the mass  $M_X^2$  is given by

$$M_X^2 = m_p^2 + 2p|t|^{1/2} \left( \sin\omega - \frac{m_d + p}{2m_d p} |t|^{1/2} \right), \quad (2)$$

where  $p$  is the incident momentum and  $|t|$ , the four-momentum transfer, is given by

$$|t| = 2m_d T, \quad (3)$$

with  $T$  the kinetic energy of the recoil deuteron. The data were normalized by using a fixed detector stack which measured elastic scattering at  $|t| = 0.043$  (GeV/c)<sup>2</sup>. The elastic  $p$ - $d$  cross section was taken to be<sup>8</sup>

$$\left. \frac{d\sigma}{dt} \right|_{el} = \frac{(\sigma_{\tau}^{pd})^2}{16\pi} (1 + \rho^2) \exp(-b|t| + ct^2), \quad (4)$$

with  $\sigma_{\tau}^{pd}$  the total  $p$ - $d$  cross section and  $\rho$  the ratio of real to imaginary part of the forward-elastic-scattering amplitude. Details are discussed in Ref. 8. We believe that the uncertainty in normalization is smaller than  $\pm 3\%$ .

The resolution in  $M_X^2$  is dominated by the uncertainty in the recoil angle,  $\Delta\omega$ . Detector size and the width of the jet limit  $\Delta\omega$  to about  $\pm 3$  mrad. It holds that

$$\Delta M_X^2 = 2p|t|^{1/2} \Delta\omega. \quad (5)$$

In order to improve the mass resolution, especially at the higher incident momenta, we used a slit to limit the extent of the jet target (along the beam direction) seen by a particular detector. This reduced  $\Delta\omega$  to  $\pm 1.2$  mrad. Furthermore, slit scattering was monitored by running a jet at low energy (50 GeV) where essentially no inelastic protons are produced over the useful kinetic energy range covered by the detector. Since the elastic scattering is so dominant, the bulk of the slit-scattered deuterons originate from the elastic peak which is (practically) independent of the incident energy. Thus the 50-GeV slit data could be used as a measure of the background present at higher energies. Use of the slit is limited to  $M_X^2 \lesssim 4$  GeV<sup>2</sup> because, to assure proper normal-

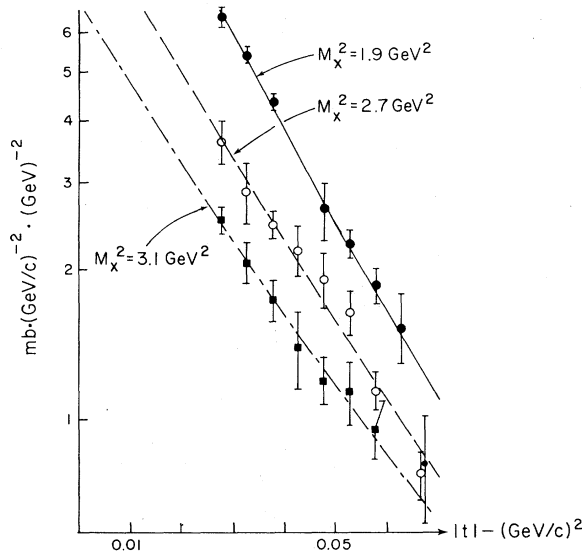


FIG. 1. Differential cross sections at 275 GeV/c versus  $t$  for  $M_x^2 = 1.9, 2.7,$  and  $3.1 \text{ GeV}^2$ .

momentum,  $p$ . In this case

$$\Delta M_x^2 = (\Delta p/p)(M_x^2 - m_p^2). \tag{5a}$$

The 50-GeV cross sections were determined without the slit and typically  $\Delta\omega \approx \pm 3 \text{ mrad}$ , but  $\Delta p = \pm 1 \text{ GeV}$ . The 180- and 275-GeV data were taken with the slit so that  $\Delta\omega \approx \pm 1.2 \text{ mrad}$  but  $\Delta p = \pm 8 \text{ GeV}$ . On the average,  $\Delta M_x^2 = \pm 0.07 \text{ GeV}^2$ .

In Fig. 1, we show typical differential cross sections at masses  $M_x^2 \approx 1.9, 2.7,$  and  $3.1 \text{ GeV}^2$ , for 275 GeV incident energy. These cross sections exhibit a steep  $t$  dependence as expected for coherent scattering from deuterons. We find no evidence for a turnover in the  $t$  distributions down to values of  $|t| \approx 0.03 \text{ (GeV/c)}^2$ . Within our  $t$  range, these distributions could be fitted by single exponentials. However, since the deuteron form factor,  $S(t)$ , determined from elastic scattering can be expressed (for small values of  $t$ ) in the form<sup>7,8</sup>

$$|S(t)|^2 = \exp(-b_0 |t| + c_0 t^2), \tag{6}$$

with<sup>8</sup>  $b_0 = 26.4 \text{ (GeV/c)}^{-2}$  and  $c_0 = 62.3 \text{ (GeV/c)}^{-4}$ , we have fitted the differential cross sections with

ization, each detector must also monitor elastic scattering (i.e., be located at small angles).

An additional contribution to the mass resolution arises from the uncertainty in the incident

TABLE I. The results of the fit to the data using the form given in Eq. (7).

$p_{\text{lab}} \rightarrow$	50 GeV/c		180 GeV/c		275 GeV/c	
	$\frac{d^2\sigma}{dt dM_x^2} \Big _{ t =0.035}$ (GeV/c) <sup>-2</sup> · GeV <sup>-2</sup>	$b_d$ (GeV/c) <sup>-2</sup>	$\frac{d^2\sigma}{dt dM_x^2} \Big _{ t =0.035}$ (GeV/c) <sup>-2</sup> · GeV <sup>-2</sup>	$b_d$ (GeV/c) <sup>-2</sup>	$\frac{d^2\sigma}{dt dM_x^2} \Big _{ t =0.035}$ (GeV/c) <sup>-2</sup> · GeV <sup>-2</sup>	$b_d$ (GeV/c) <sup>-2</sup>
1.35			1.88 ± .29		3.29 ± .24	
1.45			2.47 ± .29		3.13 ± .14	
1.55	5.55 ± .26	37.2 ± 7.2	2.83 ± .20	43.6 ± 3.6	3.75 ± .15	49.1 ± 2.3
1.65	6.60 ± .23		3.71 ± .14			
1.75	6.87 ± .36		4.38 ± .15		5.01 ± .25	
1.85	8.52 ± .39		5.09 ± .14		4.67 ± .14	
1.95	9.11 ± .47	40.1 ± 2.2	4.86 ± .16	50.4 ± 1.6	4.87 ± .15	48.2 ± 1.7
2.05	7.65 ± .44		4.72 ± .23		4.68 ± .33	
2.15	6.34 ± .40		4.26 ± .19		4.37 ± .21	
2.25	5.89 ± .71		3.78 ± .16		3.74 ± .12	
2.35	5.72 ± .47	43.4 ± 5.4	3.24 ± .12	41.8 ± 2.4	3.18 ± .14	43.4 ± 2.4
2.45	5.05 ± .43		2.78 ± .17		3.09 ± .11	
2.55	4.74 ± .69		3.04 ± .16		2.73 ± .12	
2.65	6.07 ± .51		2.85 ± .17		2.86 ± .16	
2.75	5.48 ± .73	41.7 ± 4.4	3.48 ± .19	39.9 ± 3.2	2.75 ± .17	40.7 ± 2.0
2.85	5.27 ± .45		3.27 ± .41		2.64 ± .13	
2.95	3.39 ± .34		3.22 ± .20		2.60 ± .16	
3.05	3.59 ± .28		2.71 ± .20		2.04 ± .10	
3.15	2.71 ± .30	36.1 ± 4.1			1.87 ± .10	
3.25	2.55 ± .21				1.89 ± .15	38.5 ± 2.8
3.35	2.23 ± .21				1.47 ± .10	
3.45	2.24 ± .25				1.38 ± .12	
3.55	1.76 ± .22				1.30 ± .17	
3.65	1.58 ± .20	32.8 ± 4.4			1.38 ± .12	35.0 ± 4.5
3.75	1.91 ± .41				1.37 ± .10	
3.85	2.13 ± .37				1.29 ± .11	
3.95	1.95 ± .38				1.35 ± .10	

a form similar to Eq. (6),

$$\frac{d^2\sigma}{dt dM_X^2} = A \exp[-b_d(|t| - 0.035) + c_0(t^2 - 0.035^2)]. \quad (7)$$

The parameters  $A$  and  $b_d$  were obtained from the fit, while  $c_0$  was fixed at  $c_0 = 62.3 \text{ (GeV/c)}^{-4}$ . The fit was made around the central value of our measured  $t$  range,  $|t| = 0.035 \text{ (GeV/c)}^2$ , so that the best-fit values and errors of  $A$  and  $b_d$  remain uncorrelated.

The results of the fits for  $d^2\sigma/dt dM_X^2$  at  $|t| = 0.035$  are given in Table I as a function of  $M_X^2$  and shown in Fig. 2. We note the existence of a prominent broad enhancement in the region  $M_X^2 \approx 1.9 \text{ GeV}^2$  and a smaller peak at  $M_X^2 = 2.8 \text{ GeV}^2$  which we identify with the  $N^*(1688)$  state. In Table I we also give average values for  $b_d$ . If it is assumed that the deuteron cross sections factorize as  $d\sigma(pd) = d\sigma(pp)F_d$ , where  $F_d(t)$  is the coherence factor defined as

$$F_d(t) = (\sigma_{\tau}^{pd} / \sigma_{\tau}^{pp}) |S(t)|^2, \quad (8)$$

then  $b_N \equiv b_d - b_0$  is a measure of the "slope parameter" for the diffractive dissociation of the proton on a nucleon.<sup>9</sup> We note that if  $b_0$  is treated

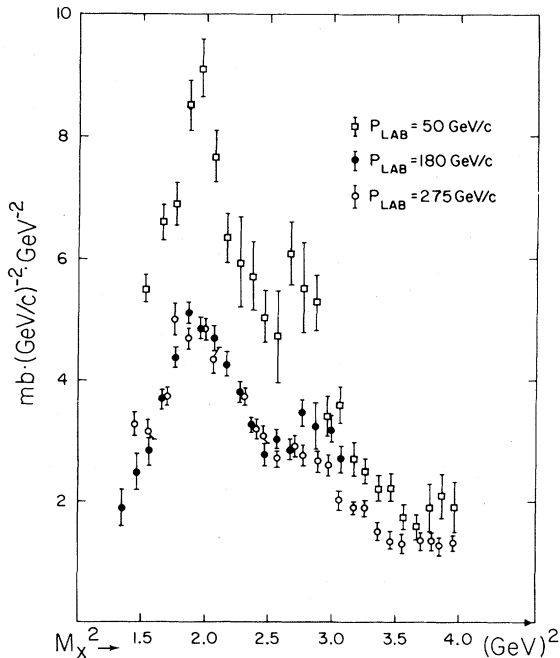


FIG. 2. Values of  $d^2\sigma/dt dM_X^2$  at  $|t| = 0.035 \text{ (GeV/c)}^2$  versus  $M_X^2$  for incident energies of 50, 180, and 275 GeV.

as a constant independent of  $M_X^2$ , the slope parameter  $b_N$  decreases from a value of  $b_N \approx 24 \text{ (GeV/c)}^{-2}$  at  $M_X^2 \approx 1.9 \text{ GeV}^2$  to  $b_N \approx 10 \text{ (GeV/c)}^{-2}$  at  $M_X^2 \approx 4.0 \text{ GeV}^2$ .

In order to compare these data with previously known results on the diffractive excitation of the proton we have divided the differential cross section by  $F_d(t)$  evaluated at the appropriate  $t$  value. If the cross section factorizes, this procedure should yield the corresponding data for  $p + p \rightarrow X + p$ . In Fig. 3(a) we show data for this reaction obtained<sup>10</sup> at 20 GeV, together with our 50- and 275-GeV data refitted about the corresponding central  $t$  value of  $0.042 \text{ (GeV/c)}^2$ . In Figs. 3(b) and 3(c), we compare our results with data for the reaction  $p + p \rightarrow X + p$  obtained<sup>6</sup> at 175 and 260 GeV, where the central  $t$  value used is  $0.025 \text{ (GeV/c)}^2$ . The agreement between the high-energy results indicates that the cross section does indeed factorize. We further observe that the general behavior of the low-mass diffractive excitation of the proton does not change its character between 20 and 300 GeV, even though the overall cross section decreases markedly with energy. If one assumes the presence of a background, as discussed in Ref. 10, the magnitude of the 1400-MeV enhancement peak changes very little with energy. The changing values of  $b_N$  and the structure in the cross section as a function of  $M_X^2$  are distinctly different from the smooth behavior for  $M_X^2 > 5 \text{ GeV}^2$  reported<sup>2</sup> in the following

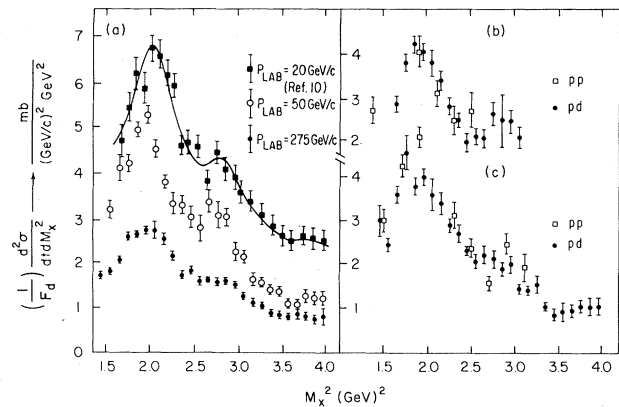


FIG. 3. (a) A comparison of our results for  $(1/F_d) \times (d^2\sigma/dt dM_X^2)|_{|t|=0.042}$  at 50 and 275 GeV with the 20-GeV  $p$ - $p$  results reported in Ref. 10. The curve is a fit reported in Ref. 10 including resonances and a "non-resonant" background. (b) A comparison of  $(1/F_d) \times (d^2\sigma/dt dM_X^2)|_{|t|=0.025}$  at 180 GeV with 175-GeV  $p$ - $p$  data (Ref. 6); (c) a similar comparison of our 275-GeV data with the 260-GeV data of Ref. 6.

Letter.

We are grateful to many members of the Fermilab staff and in particular to the personnel of the internal target section for their cooperation in the planning and execution of this experiment. We acknowledge the support of the technical staff at Rockefeller University and the University of Rochester. The Soviet members of our team express their gratitude to the U.S.S.R. State Committee for Atomic Energy and the Joint Institute for Nuclear Research, Dubna, for their generous support.

\*Work supported in part by the U. S. Energy Research and Development Administration under Contracts No. AT(11-1)-2232A and No. AT(11-1)-3065, and by the U. S. S. R. State Committee for Atomic Energy.

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<sup>1</sup>Preliminary results from this experiment are reported by Y. Akimov *et al.*, in *Proceedings of the Sev-*

*enteenth International Conference on High Energy Physics, London, England, 1974*, edited by J. R. Smith (Rutherford High Energy Laboratory, Didcot, Berkshire, England, 1975).

<sup>2</sup>Y. Akimov *et al.*, following Letter [Phys. Rev. Lett. **35**, 766 (1975)].

<sup>3</sup>V. Bartenev *et al.*, Adv. Cryog. Eng. **18**, 460 (1973).

<sup>4</sup>By the use of a 5-mm lithium-drifted detector as the second detector of a stack, the  $t$  range was extended to  $|t| \approx 0.12$  (GeV/c)<sup>2</sup> in some cases.

<sup>5</sup>Y. Akimov *et al.*, Zh. Eksp. Teor. Fiz. **48**, 767 (1965) [Sov. Phys. JETP **21**, 507 (1965)]; Y. Akimov *et al.*, Yad. Fiz. **4**, 88 (1965) [Sov. J. Nucl. Phys. **4**, 63 (1967)]; V. Bartenev *et al.*, Phys. Rev. Lett. **31**, 1088, 1367 (1973); and references given in these papers.

<sup>6</sup>V. Bartenev *et al.*, Phys. Lett. **51B**, 299 (1974).

<sup>7</sup>L. S. Zolin *et al.*, Yad. Fiz. **18**, 56 (1973) [Sov. J. Nucl. Phys. **18**, 30 (1974)].

<sup>8</sup>Y. Akimov *et al.*, "Proton-Deuteron Elastic Scattering at Small Momentum Transfer from 50 to 400 GeV/c" (to be published).

<sup>9</sup>We point out that, although  $b_0$  as extracted from elastic scattering is strongly correlated to  $c_0$ , the values for  $b_N$  and for the extracted nucleon cross sections are not affected by variations of the parameters  $b_0$  and  $c_0$  within the constraint imposed by the elastic-scattering data (Refs. 7 and 8).

<sup>10</sup>R. M. Edelstein *et al.*, Phys. Rev. D **5**, 1073 (1972).

## Diffraction Dissociation of High-Energy Protons in $p$ - $d$ Interactions\*

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(Received 1 May 1975)

We report results from a measurement of the inclusive process  $p + d \rightarrow X + d$  in the region  $0.03 < |t| < 0.12$  (GeV/c)<sup>2</sup> and  $5 \text{ GeV}^2 < M_X^2 \lesssim 0.11 p_{\text{lab}}$  for incident proton momenta from 150 to 400 GeV/c. We find that in this region, the differential cross section  $d^2\sigma/dt dM_X^2$  varies only slowly with energy, falls exponentially with  $|t|$ , and behaves to a good approximation as  $1/M_X^2$ . The measurement was performed at Fermilab by detecting slow-recoil deuterons from a deuterium-gas-jet target placed at the internal beam of the accelerator.

As part of an experimental study<sup>1,2</sup> of the low-four-momentum-transfer interaction of high-energy protons with a deuterium-gas-jet target in the internal beam at Fermilab, we have measured the differential cross section  $d^2\sigma/dt dM_X^2$  for the inelastic inclusive reaction

$$p + d \rightarrow X + d \quad (1)$$

in the region  $0.03 < |t| < 0.12$  (GeV/c)<sup>2</sup> and  $(5 \text{ GeV}^2 / s < M_X^2 / s \lesssim 0.03$ , where  $s \approx 2m_d p_{\text{lab}}$ , for incident

proton momenta from 150 to 400 GeV/c. In this region of small  $|t|$  and small  $M_X^2/s$ , Reaction (1) is expected to be dominated by diffraction dissociation of the incoming proton. Results on the excitation of protons into the resonance region ( $M_X^2 < 5 \text{ GeV}^2$ ) are presented in the preceding Letter.<sup>2</sup> Here we discuss the diffraction dissociation of protons into the continuum of states with  $M_X^2 > 5 \text{ GeV}^2$ , up to  $M_X^2/s \approx 0.03$  or  $M_X^2 \sim 40 \text{ GeV}^2$  for our highest proton momentum.