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DIFFERENTIAL CROSS SECTIONS FOR THE REACTIONS $p + p \rightarrow D + \pi^+$ AND $p + p \rightarrow D + \rho^+$ AT 21 GeV/c

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ABSTRACT

Results are presented from an experiment in which high-energy deuterons, produced by proton-proton interactions at 21.1 GeV/c incident momentum, were detected over a range of angles from 12.5 mrad to 60 mrad in the laboratory system. From the momentum spectra of the deuterons, the final states $D + \pi^+$ and $D + \rho^+$ have been identified. The angular distribution for these reactions are presented and compared with previous data at lower energies.

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The angular distribution of the two-body reaction $p + p \rightarrow D + \pi^+$ (or its inverse $\pi^+ + D \rightarrow p + p$) has been investigated extensively at incident proton momenta below about 4 GeV/c[1,2]. Other studies[3] report the differential cross section as a function of momentum, up to about 12 GeV/c, at a fixed laboratory production angle and some cross sections have been measured[4] at isolated points.

This letter reports new data on the angular distributions of the reactions $p + p \rightarrow D + \pi^+$ and $p + p \rightarrow D + \rho^+$, measured at 21.1 GeV/c incident proton momentum. In addition some data are presented on the momentum spectrum of deuterons at a fixed lab angle of 40 mrad. Preliminary results have been reported[5] at the 1968 Vienna Conference.

High-energy deuterons produced in a 10 cm long liquid hydrogen target placed in a long pulse extracted proton beam of the CERN proton synchrotron, were detected using a magnetic spectrometer of good momentum resolution ($\approx \pm 0.2\%$). The full momentum acceptance of the spectrometer $\Delta p/p$ was 2%. Five scintillation counters placed at the dispersive focus, each accepting a momentum band of 0.4%, served to define the particle momentum. The production angle could be varied over a range of laboratory angles from 12.5 mrad to 70 mrad. Further details of the spectrometer are given elsewhere[6].

The beam intensity was monitored by a secondary emission chamber placed 2 metres ahead of the hydrogen target, and by two counter telescopes detecting secondary particles produced in the target. An absolute calibration was obtained by periodically measuring the Na^{24} activity induced in aluminium foils placed in the beam behind the secondary emission monitor. The Na^{24} activation cross section[7] used was 8.6 ± 0.5 mb.

Deuterons were identified by two independent Čerenkov counter techniques. One used three threshold Čerenkov counters[8] to detect protons and lighter particles and the resultant signals were used in anticoincidence to veto all charged particles except the deuterons. The second technique used a DISC differential Čerenkov counter[9], with the velocity band tuned to accept only deuterons. Both these methods of identification gave consistent results, which was a valuable check on the performance of the equipment.

Deuteron momentum spectra were measured at 12.5, 20, 30, 40, 50 and 60 mrad. At all angles except 40 mrad only the high momentum parts of the spectra, above about 19 GeV/c, were covered. At 40 mrad measurements were made down to 8 GeV/c. The flux of particles through the spectrometer was limited by a collimator of variable aperture in order to keep electronic dead-time effects small. The fraction of deuterons in the beam depended strongly on production angle, ranging between about 10^{-3} and 5×10^{-5}. It was found that the optimum angle for measuring a detailed spectrum was 40 mrad and hence most effort was spent at this angle. The results are shown in Figs. 1 and 2.

The final states $D\pi^+$ and $D\rho^+$ are clearly seen as peaks of approximately equal area in Fig. 1. By comparing the position of the ρ peak to the position of the elastic proton peak, the ρ mass is found to be 760 ± 25 MeV. In addition, there is further structure of comparable cross section in the region of missing mass 1.0 to 1.4 GeV which may be identified with the production of the A_1 and A_2 meson resonances.

Corrections to the cross sections have been applied for absorption and geometrical loss at the end of the spectrometer. The combined correction amounted to a multiplicative factor of 1.4 at 21 GeV/c increasing to 2.4 at 8 GeV/c. For the high momentum end of the spectra the empty target background was typically as shown in Fig. 1. At lower momenta a correction of 20% was applied.

Some typical statistical errors are shown in Fig. 1. In Fig. 2 they are smaller than the points. There is a systematic uncertainty caused by the rather large corrections needed and by the 7% error in the value of the Na^{24} production cross section in aluminium, used in the absolute calibration. This systematic uncertainty is estimated to be ± 12% at 21 GeV/c, increasing to ± 25% at 8 GeV/c, where the corrections were more important.

The two-body differential cross sections were obtained by evaluating the area of the peaks above the extrapolated smooth continuum. The results of this evaluation are given in the table in the form of centre-of-mass differential cross sections together with the corresponding value of the transverse momentum. The result of a measurement at 19.2 GeV/c incoming momentum and 40 mrad production angle is also given. Finally, a point at 19.4 GeV/c, 25 mrad is quoted resulting from a preliminary measurement[10].

Figure 3a shows the centre-of-mass differential cross sections for both $p + p \rightarrow D + \pi^+$ and $p + p \rightarrow D + \rho^+$ plotted as functions of the transverse momentum $p_\perp = p \sin\vartheta$. Both reactions have strikingly similar cross sections and can be fitted by

$$\left(\frac{d\sigma}{d\Omega}\right) = A \exp\left(\frac{-p_\perp}{b}\right) \qquad (1)$$

with

$A = (2.8 \pm 0.5) \times 10^{-31}\ \mathrm{cm^2/sr}$, $\quad b = 0.192 \pm 0.008$ GeV/c

for $\quad p + p \rightarrow D + \pi^+$ and

$A = (3.2 \pm 0.8) \times 10^{-31}\ \mathrm{cm^2/sr}$, $\quad b = 0.183 \pm 0.010$ GeV/c

for $\quad p + p \rightarrow D + \rho^+$.

Because of the near equality of the two fits, only the first one is drawn in Fig. 3a.

Integration of equation (1), and multiplication by two to take account of the equal contribution from the backward hemisphere, yields the total cross sections

$$\sigma(pp \rightarrow D\pi^+) = (15.1 \pm 1.5) \times 10^{-33}\ \mathrm{cm^2}$$

$$\sigma(pp \rightarrow D\rho^+) = (15.9 \pm 2.4) \times 10^{-33}\ \mathrm{cm^2}.$$

The uncertainty in these cross sections arises from the fit (1). In addition there is the common systematic error of ±12%.

The equality of the $D\pi^+$ and $D\rho^+$ cross sections seems to be, at first sight, surprising as in general it appears that ρ production[11] in p - p interactions is not very strong.

Figure 3b shows the data displayed in the form $d\sigma/dt$ as a function of $|t'| = |t - t_{min}|$, where t is the square of the four-momentum transfer from the proton to the deuteron, and t_{min} is the value of t for deuteron production at zero degree. The data clearly cannot be fitted by a single exponential, but indicate a peaking in the forward direction, superimposed on an exponential intermediate part, roughly $\sim e^{-3|t'|}$, followed by a flattening beyond $|t'| = 1\ \mathrm{GeV}^2$.

The data of Heinz et al.[1] on the reaction $p + p \to D + \pi^+$ at 3.62 GeV/c have been plotted in both Figs. 3a and 3b for comparison. Cross sections obtained by detailed balance from the inverse process $\pi^+ + D \to p + p$ measured by Dekkers et al.[2] are in close agreement with the more precise data of Heinz et al. and so have been omitted for clarity. Figure 3 shows that the angular distributions measured at 3.6 GeV/c and at 21.1 GeV/c are similar in that both can be fitted by an exponential in transverse momentum although the slopes of the two distributions are somewhat different.

Comparison of the low and high energy data exhibits the strong energy dependence of the $D\pi^+$ reaction at fixed $p_\perp$ or t'. The energy dependence of the cross section at essentially fixed $p_\perp \simeq 0.10$ GeV/c is given by the data of Anderson et al.[3] for laboratory momenta between 3.4 and 12.3 GeV/c. Anderson's results show that above a small shoulder at 6 GeV/c (square of c.m. energy $s \simeq 13\ \mathrm{GeV}^2$) the cross section follows a power law in s

$$\left(\frac{d\sigma}{d\Omega}\right)_{p_\perp \simeq 0.10} \sim s^{-n} \qquad (2)$$

with $n \simeq 3$ up to $s \simeq 25\ \mathrm{GeV}^2$.

This dependence fits the results of the present experiment ($s = 41.4\ \mathrm{GeV}^2$) extrapolated to $p_\perp = 0.10$ GeV/c to within a factor of two.

Figure 3a and relation (2) suggest that the cross sections for $p + p \rightarrow D + \pi^+$ above a laboratory momentum of about 3.5 GeV/c can be described quite well by

$$\left(\frac{d\sigma}{d\Omega}\right) \sim s^{-n} \quad \exp\left(\frac{-p_\perp}{b}\right) \qquad (3)$$

with $n \simeq 3$ and $b \simeq 0.20$ GeV/c.

The cross sections quoted in reference 4 also fit reasonably well to relation (3) although it should be remembered that this equation is only approximately valid as evinced by the shoulder at 6 GeV/c and by the variation of the parameter b between 3.6 and 21.1 GeV/c.

Figure 4 shows the energy dependence of the total cross section for $p + p \rightarrow D + \pi^+$. The points are the cross sections obtained by integration of the available high energy angular distributions (refs. 1 and 2 and the present experiment). The cross-hatched region indicates estimates of the total cross section obtained from the points of Anderson et al.[3]) using the $p_\perp$ dependence of equation (1). The upper and lower bounds result from taking $b = 0.26$ GeV/c and $b = 0.19$ GeV/c, respectively. The change in slope, indicated at around $s = 12$ GeV^2, corresponds to the shoulder found by Anderson et al. in the forward differential cross section at $\simeq 6$ GeV/c laboratory momentum.

Considering the upper end of Fig. 4 between $s \simeq 12$ GeV^2 and the point measured in the present experiment at $s = 41$ GeV^2 the fall in the total cross section can be represented by

$$\sigma \sim s^{-m} \qquad (4)$$

where m is about 4. Because of the lack of data it is not possible to be more accurate in this dependence especially as it may well be that such a simple functional form is not very precise. However, the energy dependence is certainly very strong and according to a classification of Morrison[12]), such a strong energy dependence is a signature of baryon exchange.

A one-pion exchange calculation of the $p + p \rightarrow D + \pi^+$ reaction in the 3 GeV/c region by Yao[13] and recently continued to higher energy by Anderson et al.[3] and Brown[14] relates the reaction under discussion to the cross section for backward pion-proton scattering which has been successfully analysed in terms of Reggeized baryon exchange. These calculations were in qualitative agreement with the previous data and evaluation at 21 GeV/c shows that the model also gives approximate agreement with the present results. As noted by Anderson et al.[3] lack of pion-proton backward charge exchange scattering cross sections prevents more precise considerations. In a qualitative sense one may note that if the $D\pi^+$ reaction is closely related to backward $\pi^+ - p$ scattering it might be expected that the structure observed[15] in the scattering angular distribution should be reflected in the deuteron production angular distribution. The number of data points collected in the present experiment do not allow any conclusion on this question, unfortunately.

If the $D\pi^+$ process may be related to backward pion-proton scattering it is interesting to note in connection with the equality of the $D\pi^+$ and $D\rho^+$ cross sections, that the reactions[16] $\pi^- + p \rightarrow \pi^- + p$ and $\pi^- + p \rightarrow \rho^- + p$ near 180° at 8 GeV/c and 16 GeV/c also have rather similar cross sections and angular distributions. Furthermore there is the suggestion[17] that the reactions $\pi^- + p \rightarrow A_1^- + p$ and $\pi^- + p \rightarrow A_2^- + p$ at 180° are also similar to elastic scattering.

In conclusion, the differential cross sections for the reactions $p + p \rightarrow D + \pi^+$ and $p + p \rightarrow D + \rho^+$ have been measured at an incident momentum of 21.1 GeV/c and are found to be identical within the errors of this experiment. Furthermore, structure in the deuteron missing mass spectrum may be tentatively attributed to production of the A_1 and A_2 mesons.

The $D\pi^+$ and $D\rho^+$ cross sections have a form consistent with an exponential fall-off with transverse momentum. A comparison between the present data on the reaction $p + p \rightarrow D + \pi^+$ and earlier data at lower energies reveals a close similarity in the angular distributions and a strong energy dependence, suggestive of baryon exchange processes.

The deuteron spectrum given in Fig. 2 shows that the maximum cross section for deuteron production at 10 GeV/c is an order of magnitude bigger than that[18] for the production of antiprotons at the same laboratory angle and secondary particle momentum. Useful beams of high energy deuterons are therefore feasible.

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Table 1

Centre-of-mass differential cross sections for $p + p \rightarrow D + \pi^+$ and $p + p \rightarrow D + \rho^+$. In addition to the statistical error shown, there is a scale error of 12%

p_o (GeV/c)	Θ_{lab} (mrad)	$p + p \rightarrow D + \pi^+$			$p + p \rightarrow D + \rho^+$		
		$p_\perp$ (GeV/c)	$(d\sigma/d\Omega)$ * (cm^2/ster)	Error %	$p_\perp$ (GeV/c)	$(d\sigma/d\Omega)$ * (cm^2/ster)	Error %
21.1	12.5	0.269	7.73 E-32	15	0.265	7.78 E-32	15
	20	0.429	2.82 E-32	15	0.422	2.55 E-32	15
	30	0.639	1.031 E-32	15	0.630	1.18 E-32	15
	40	0.845	3.32 E-33	15	0.833	4.26 E-33	15
	50	1.045	9.45 E-34	20	1.030	8.13 E-34	20
	60	1.238	5.54 E-34	20	1.219	4.14 E-34	20
19.2	40	0.771	4.85 E-33	15	0.758	4.94 E-33	15
19.4	25	0.49	2.0 E-32	30			

* The expression E-32 indicates a multiplicative factor of 10^{-32}.

REFERENCES

1. T.H. Fields, J.G. Fox, J.A. Kane, R.A. Stallwood, and R.B. Sutton, Phys.Rev. 95, 638 (1954).

   M.G. Mescheryakov, B.S. Neganov, N.P. Bogachev and V.M. Sidorov, Dokl.Akad.Mauk. SSSR 100 (1955) 673.

   D.V. Bugg, A.J. Oxley, J.A. Zoll, J.G. Rushbrooke and V.E. Barnes, Phys.Rev. 133, B1016 (1964).

   K.R. Chapman, T.W. Jones, Q.H. Khan, J.S.C. McKee, H.B. Van Der Raay and Y. Tanimura, Phys.Letters 11, 253 (1964).

   R.M. Heinz, O.E. Overseth, D.E. Pellett and M.L. Perl, Phys.Rev. 167, 1232 (1968).

2. D. Dekkers, B. Jordan, R. Mermod, C.C. Ting, G. Weber, T.R. Willitts, K. Winter, X. de Bouard and M. Vivargent, Phys.Letters 11, 161 (1964).

3. F. Turkot, G.B. Collins and T. Fujii, Phys.Rev.Letters 11, 474 (1963).

   G. Cocconi, E. Lillethun, J.P. Scanlon, C.A. Ståhlbrandt, C.C. Ting, J. Walters and A.M. Wetherell, Phys.Letters 7, 222 (1963).

   H.L. Anderson, M. Dixit, H.J. Evans, K.A. Klare, D.A. Larson, M.V. Sherbrook, R.L. Martin, K.W. Edwards, D. Kessler, D.E. Nagle, H.A. Thiessen, C.K. Hargrove, E.R. Hincks and S. Fukui, Phys.Rev.Letters 21, 853 (1968).

4. N.W. Reay, A.C. Melissinos, J.T. Reed, T. Yamanouchi, and L.C.L. Yuan, Phys.Rev. 142, 918 (1966).

   R.C. Lamb, R.A. Lundy, T.B. Novey, D.D. Yovanovitch and R. Lander, Phys.Rev.Letters 17, 100 (1966).

   K. Ruddick, L.G. Ratner, K.F. Edwards, C.W. Akerlof, R.H. Hieber and A.R. Krisch, Phys.Rev. 165, 1442 (1968).

   W.F. Baker, E.W. Jenkins, A.L. Read, A.D. Krisch, J. Orear, R. Rubinstein, D.B. Scarl and B.T. Ulrich, Phys.Rev. 136, B779 (1964).

5. Report of G. Bellettini, pp.353, Proc.Int.Conf. on High-Energy Physics (Vienna 1968).

6. J.V. Allaby, F. Binon, A.N. Diddens, P. Duteil, A. Klovning, R. Meunier, J.P. Peigneux, E.J. Sacharidis, K. Schlüpmann, M. Spighel, J.-P. Stroot, A.M. Thorndike, A.M. Wetherell, Phys.Letters 28B, 67 (1968).

7. J.B. Cumming, Ann.Rev.Nucl.Science 13, 261 (1963).

8. M. Vivargent, G. von Dardel, R. Mermod, G. Weber and K. Winter, Nucl.Instr. and Methods 22, 165 (1963).

9. P. Duteil, L. Gilly, R. Meunier, J.-P. Stroot, and M. Spighel, Rev.Sci.Inst. 35, 1523 (1964).

10. J.V. Allaby, G. Bellettini, G. Cocconi, A.N. Diddens, S. Gjesdal, G. Matthiae, E.J. Sacharidis, A. Silverman, A.M. Wetherell, J.P. Garron, L. Hugon, R. Meunier, M. Spighel, J.-P. Stroot and P. Duteil, CERN NP Internal Report 66-2 (1966).

11. H.L. Anderson, S. Fukui, D. Kessler, K.A. Klare, M.V. Sherbrook, H.J. Evans, R.L. Martin, E.P. Hincks, N.K. Sherman and P.I.P. Kalmus, Phys.Rev.Letters 18, 89 (1967).

E.L. Hart, R.I. Louttit and T.W. Morris, Phys.Rev.Letters 9, 133 (1962); G. Alexander, O. Benary, G. Czapak, B. Haber, N. Kidron, B. Reuter, A. Shapira, E. Simoulou and G. Yekutieli, Phys.Rev. 154, 1284 (1967); A.P. Colleraine and U. Nauenberg, Phys.Rev. 161, 1387 (1967); C. Caso, F. Conte, G. Tomasini, L. Casè, L. Mosca, S. Ratti, L. Tallone-Lombardi, I. Bloodworth, L. Lyons and A. Norton, Nuovo Cimento 55, 66 (1968).

12. D.R.O. Morrison, Physics Letters 22, 528 (1966).

13. T. Yao, Phys.Rev. 134, B454 (1964).

14. D.J. Brown, Nucl. Physics B7, 37 (1968).

15. J. Orear, D.P. Owen, F.C. Peterson, A.L. Read, D.G. Ryon, D.H. White, A. Ashmore, C.J.S. Damerell, W.R. Frisken, and R. Rubinstein, Phys.Rev.Letters 21, 389 (1968).

16. E.W. Anderson, E.J. Bleser, H.R. Blieden, G.B. Collins, D. Garelick, J. Menes, F. Turkot, D. Birnbaum, R.M. Edelstein, N.C. Hien, T.J. McMahon, J. Mucci and J. Russ, Phys.Rev.Letters 22, 102 (1969).

17. Report by E.W. Anderson et al. submitted to Vienna Conference.

18. J.V. Allaby, F. Binon, A.N. Diddens, P. Duteil, A. Klovning, R. Meunier, J.P. Peigneux, E.J. Sacharidis, K. Schlüpmann, M. Spighel, J.-P. Stroot, A.M. Thorndike, and A.M. Wetherell, referred to in report of O. Czyzewski, pp. 376, Proc.Int. Conf. on High-Energy Physics (Vienna 1968).

FIGURE CAPTIONS

1. Deuteron momentum spectrum obtained at a laboratory angle of 40 mrad. The crossed points indicate the empty target background. The broken line indicates the hand-drawn fit to the smooth continuum used to extract the two-body differential cross sections. The inset shows the spectrum after subtraction of this continuum.

2. The deuteron spectrum at 40 mrad extended to lower momenta. The systematic error in the points is 12%, at the highest momenta, increasing to 25% at the lowest.

3. Centre-of-mass differential cross sections as a function of a) the transverse momentum of the deuteron and b) the square of the four-momentum transfer from proton to deuteron for both $p + p \rightarrow D + \pi^+$ and $p + p \rightarrow D + \rho^+$. Data for the first reaction at 3.62 GeV/c are shown for comparison.

4. The total cross section for the reaction $p + p \rightarrow D + \pi^+$ as a function of the square of the c.m. energy s. The cross hatched region indicates the trend of the total cross section estimated from the data of Anderson et al.[3]

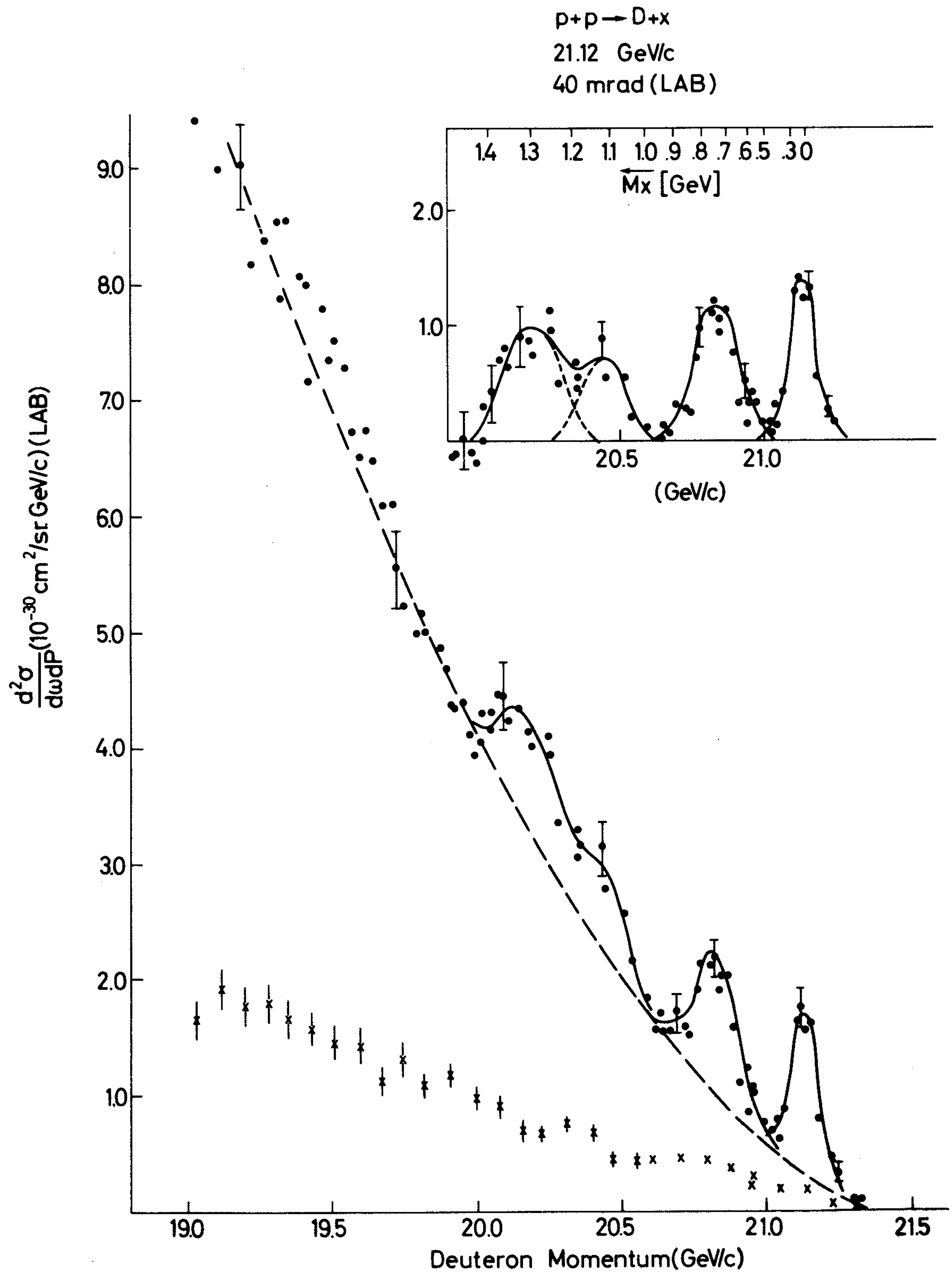

p+p → D+x
21.12 GeV/c
40 mrad (LAB)
1.4 1.3 1.2 1.1 1.0 .9 .8 .7 .6 .5 .3 0
Mx [GeV]
2.0
1.0
20.5
21.0
(GeV/c)
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
$\frac{d^2\sigma}{d\omega dP}$ (10^{-30} cm^2/sr GeV/c) (LAB)
19.0
19.5
20.0
20.5
21.0
21.5
Deuteron Momentum (GeV/c)

Fig : 1

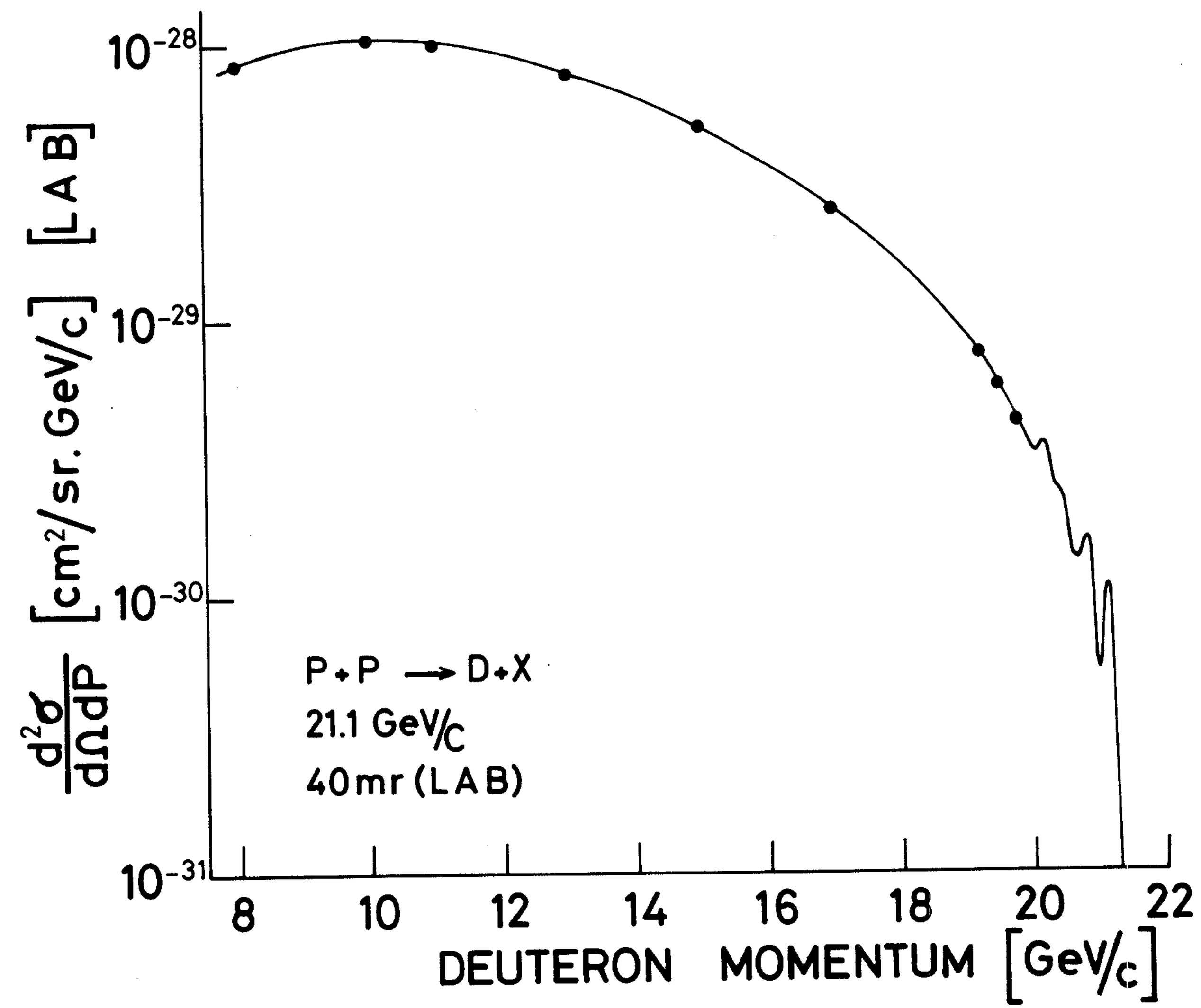
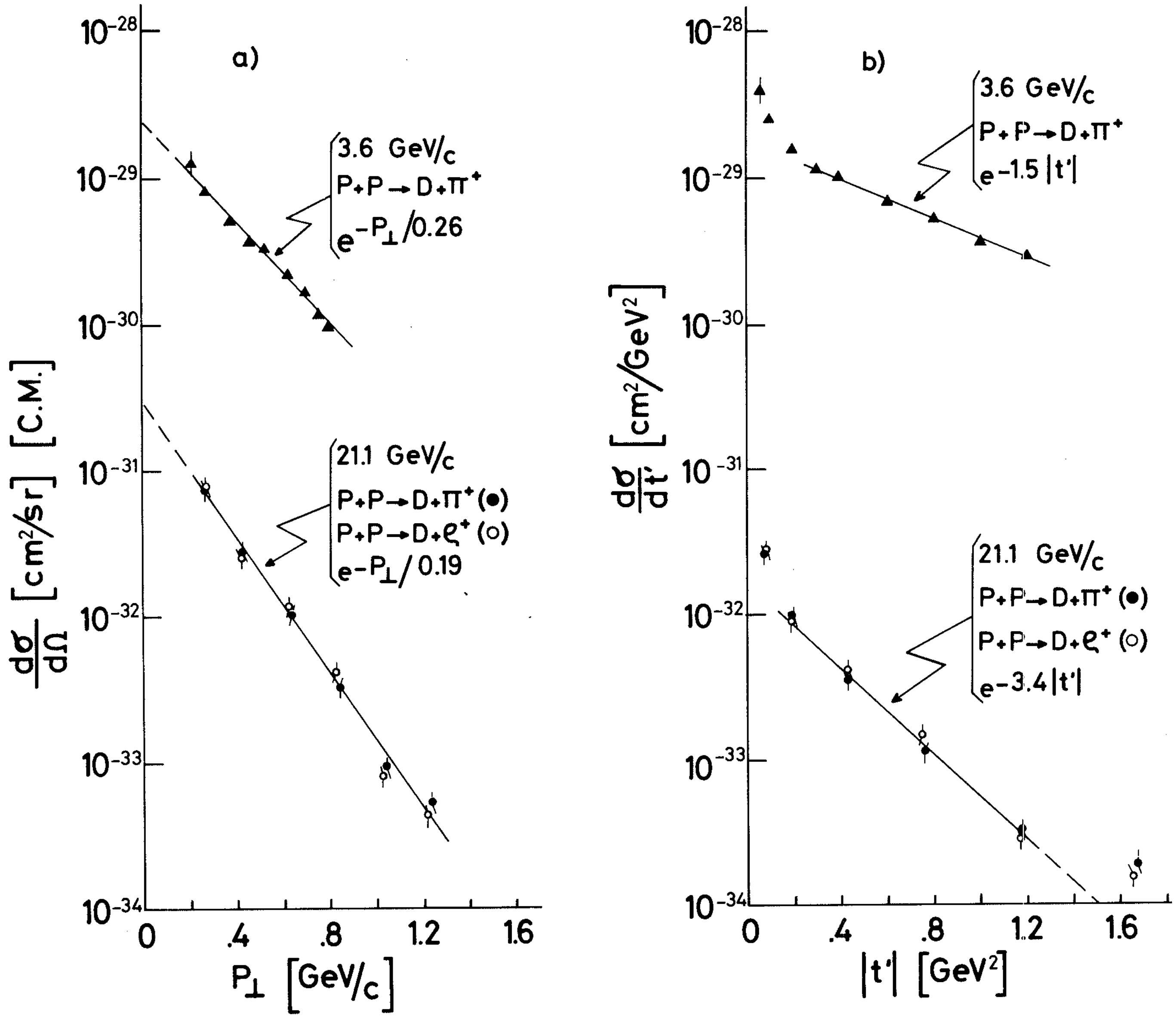
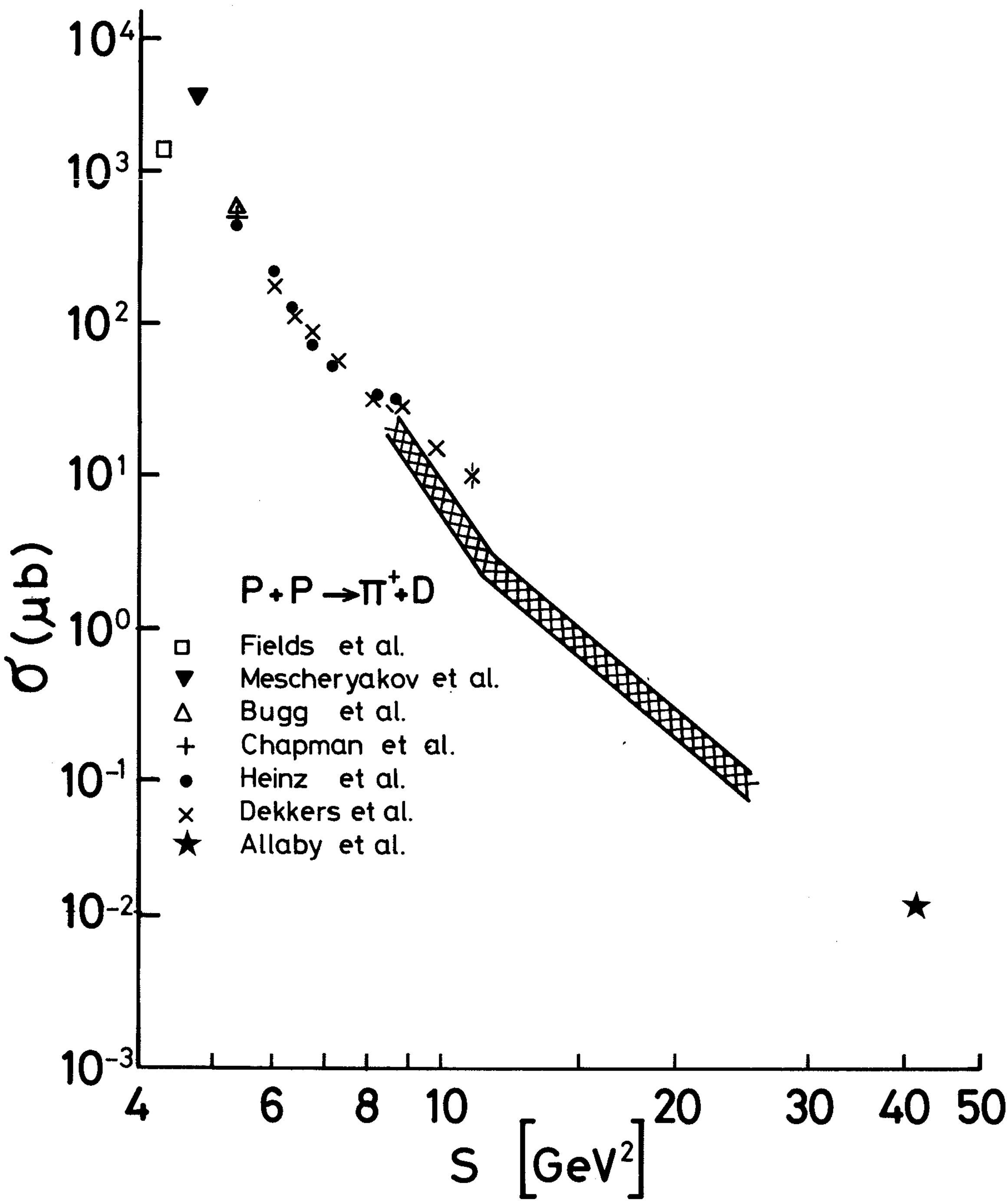

10^-28
10^-29
10^-30
10^-31
d²σ/dΩdP [cm²/sr. GeV/c] [LAB]
P+P → D+X
21.1 GeV/C
40mr (LAB)
8
10
12
14
16
18
20
22
DEUTERON MOMENTUM [GeV/c]

Fig: 2



a)
3.6 GeV/c
P+P → D+π+
e−P⊥/0.26
21.1 GeV/c
P+P → D+π+ (●)
P+P → D+ρ+ (○)
e−P⊥/0.19
dσ/dΩ [cm²/sr] [C.M.]
P⊥ [GeV/c]
b)
3.6 GeV/c
P+P → D+π+
e−1.5|t'|
21.1 GeV/c
P+P → D+π+ (●)
P+P → D+ρ+ (○)
e−3.4|t'|
dσ/dt' [cm²/GeV²]
|t'| [GeV²]

Fig: 3



10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
σ (μb)
P + P → π⁺ + D
Fields et al.
Mescheryakov et al.
Bugg et al.
Chapman et al.
Heinz et al.
Dekkers et al.
Allaby et al.
4
6
8
10
20
30
40
50
S [GeV²]

Fig: 4