FR8601183

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IPNO-DRE-84-38

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. BERTHET, R. FRASCARIA, J.P. DIDELEZ, Ch.F. PERDRISAT* and G. PIGNAULT
nstitut de Physique Nucléaire B.P. n°1 — 91406 ORSAY (FRANCE)

. BANAIGE, J. BERGER, L. GOLDZAHL and F. PLOUIN
RS4 91191 GIF-SUR-YVETTE (FRANCE)

. FABBRI, P. PICOZZA and L. SATTA
NFN Frascati (ITALY)

. BOIVIN LNS 91191 GIF-SUR-YVETTE (FRANCE)

. YONNET
niversité de Caen (14) and LNS 91191 GIF-SUR-YVETTE (FRANCE)

UNIVERSITE PARIS-SUD
I.P.N. BP n° 1 - 91406 ORSAY

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INFN Frascati (ITALY)

M. BOIVIN   LNS 91191 GIF-SUR-YVETTE (FRANCE)

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P. Berthet, R. Frascaria, J.P. Didelez, Ch.F. Perdrisat* and G. Pignault
Institut de Physique Nucléaire B.P. N° 1 - 91406 ORSAY (FRANCE)

J. Banaigs, J. Berger, L. Goldzahl and F. Plouin
ER54 91191 GIF-sur-YVETTE (FRANCE)

F. Fabbri, P. Picozza and L. Satta
INFN Frascati (ITALY)

M. Boivin
LNS 91191 GIF-sur-YVETTE (FRANCE)

J. Yonnet
Université de Caen (14) and LNS 91191 GIF-sur-YVETTE (FRANCE)

ABSTRACT

The production of π° and η° mesons in the reactions $pd \rightarrow \pi^\circ\tau$ and $pd \rightarrow \eta^\circ\tau$ has been studied at very backward angles for kinetic proton energies T_p ranging from 0.92 to 2.6 GeV. The excitation functions at $\theta_\pi = \theta_\eta = 180°$ display large structures which might be related to baryonic (Δ and N^*) excitations in the intermediate state.

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* On leave from the College of William and Mary, Williamsburg 23185 Va (USA).

I - INTRODUCTION

In the energy domain of the elementary baryonic excitations of a nucleon, nuclei could exhibit a complex excitation spectrum of various multibaryonic resonances (Ref. 1). The region of the $\Delta(1232)$ has been studied in various π - and γ - induced reactions (Ref. 2, 3, 4). From the study of the reaction $He^4(\gamma,\pi^- p)$ of Ref. 4, it has been suggested that the rather small resonance observed could be a resonant state formed by the Δ with other nucleons. The main difficulty with this kind of experiments is to separate the quasifree Δ production from a coherent Δ production mechanism. In this sense, the choice of kinematical conditions emphasizing multibaryon mechanism is of great importance : that is the case of very backward meson production where the single particle contribution is reduced and many nucleons solicited to share the transferred momentum. In the case of proton induced reactions, head-on collision can lead to the fusion of the p + A system in S-channel resonances with rather low angular momenta. The p + d system is the lower N-A system available and a previous $p + d \rightarrow t + \pi^+$ experiment, studying the excitation function at $\theta_\pi = 180°$ in the energy range $0.6 \leq T_p \leq 1.5$ GeV (Ref. 5) revealed a significant structure centered at $T_p = 1.2$ GeV corresponding to 700 MeV excitation energy in the p + d system.

The present work is a further study of the pd-system including new data for the $\tau\pi^0$ and $\tau\eta^0$ final states which we hope will shed light on the interesting problem of identifying the baryonic states responsible for the rich structure observed in the excitation functions. The $pd \rightarrow \tau\pi^0$ reaction at very backward angles has been measured to 2.3 GeV.

To clarify the mechanism involved in the backward π-meson production, the η^0-meson (which is also a $J^\pi = 0^-$ meson) production has been also extensively studied from threshold ($T_p = 0.897$ GeV) to 2.6 GeV. Before this experimental study few data existed at very backward angles (Ref. 6).

The apparatus is described in part II and the data are presented in part III. The predictions obtained from two models of the reaction $pd \rightarrow \tau\ \pi^0$ (or $t\pi^+$) are discussed in part IV. A discussion of the several enhancements observed for the $\tau\pi^\circ$ and $\tau\eta^\circ$ final states in terms of baryonic resonances is in part V. Part VI contains the conclusions.

II - EXPERIMENTAL PROCEDURE

Protons accelerated in the SATURNE synchrotron were directed onto a cryogenic liquid deuterium target 600 mg.cm^{-2} thick. SATURNE can deliver protons in the energy range 0.2 to 2.9 GeV. The SPES IV spectrometer was tuned to detect τ's (^{3}He' s) at angles near 0°. For the $\tau\pi^\circ$ final states the angles were 0,1 and 2°. For η°-production data were obtained at angles between 0 and 6°. The momentum of the detected τ determines the invariant mass of the unobserved meson.

The SPES IV facility and its detection system have been described in earlier publications (Ref. 5). An image of the target is formed at an intermediate focus 16 m from the target, and a second image at a final focus 32 m away from the target. Scintillation hodoscopes located both at the intermediate focus and at the final focus provide pulse-height and time-of-flight information for each event. The final focal plane hodoscope is multilayered and for each particle the energy loss is determined 4 times. The momentum resolution as defined by the size of the fine step scintillator array is 0.2 % and the total relative momentum acceptance is 7 %. Digitizing and storing of all pulse-height and time-of-flight signals allow one to replay the data and apply assorted cuts on these parameters for optimum particle mass identification. A typical time resolution of 0.8 ns on the 16 m flight path, combined with the highly redundant pulse-height information, provide an excellent background rejection.

An example of the raw data is shown in figure 1 a, which displays the number of events in each element of the focal plane, here directly calibrated as p/Z, for protons of 2 GeV. Even in the raw data the η°-peak is quite apparent ; after off-line analysis the continuous background is considerably reduced as seen in figure 1 b, and the $\eta_\circ$-peak has become prominent. The remaining flat continuum must be due to 2- and 3-pion final states. The two-body cross section $d\sigma/d\Omega$ for $\tau\eta^\circ$ (and similarily $\tau\pi^\circ$) final states is calculated from the number of events in the peak, after subtraction of a smooth background fitted to the continuum left-and right from the η^0 (π^0)- peak.

The beam current was typically 2 to 5 × 10^{11} protons per burst, and monitored by 3 telescopes each comprising 3 plastic scintillators ; two telescopes were viewing a very thin CH_2 films upstream from the deuterium target, and the third was aimed at the deuterium target itself. Additionally, a secondary electron monitor was used. Absolute calibrations of the monitors were made at each beam energy by activation measurement from $^{12}C(p,pn)^{11}C$. The variation of the monitor stability during the taking of the data and the uncertainties in the absolute calibration, target thickness and solid angle lead to a total systematic error of ± 8 %.

III - THE RESULTS

The results of the present investigation include cross sections for 0 or 0.5° emission of the triton in $pd \rightarrow t\pi^+$ for proton energies from 0.6 to 1.5 GeV in steps of 0.1 GeV, which have been presented earlier in ref. 5, and are shown in table I. The so far unpublished results for $pd \rightarrow \tau\pi^0$, at proton energies of 0.92, 1.65, 1.85, 2.0 and 2.3 GeV for τ detected at 0, 1 or 2° are shown in table II. The 0° results are shown in figure 2, where the $t\pi^+$ cross sections have been divided by a factor of 2, as should be the case if isospin conservation is valid. The entirely new results for the $\tau\eta^0$ final state are shown in table III. They cover the energy range 0.92 to 2.6 GeV in 9 steps ; at several of these energies the angular distribution has been measured out to 6° in the laboratory for the τ. The 0° cross sections (or extrapolated values at the 3 highest energies) are shown in figure 2. A discussion of the qualitative differences between the excitation functions for π^0 and η^0 is to be found in part V. Beside the fact that the threshold for η^0 production occurs where the π^0 cross section is at a minimum, it should be noted that both reactions show a large enhancement at 1.6 (T_p = 1.2 GeV) to 1.7 GeV (T_p = 1.35 GeV) proton energy. Furthermore the η^0 excitation function, but not the π^0 one, contains a second peak near 1.92 (T_p = 1.75 GeV) to 2.02 (T_p = 1.85 GeV).

IV - PION DATA COMPARED TO MODEL CALCULATIONS

Concerning the π production, different models have been used in the region of the $\Delta(1232)$ resonance ($370 < T_p < 600$ MeV) to interpret the cross sections and the asymetries (Ref. 7). None of these were able to reproduce the backward pion production. In the following, we try to interpret the $\theta_\pi = 180°$ excitation function of the reaction $pd \to t\pi^+$ from $T_p = 0.4$ to 2.3 GeV using two different models.

i) - the model of Locher and Weber (Ref. 8), where the $pd \to t\pi^+$ cross section is expressed in terms of the $pp \to d\pi$ elementary interaction multiplied by an inelastic form factor F, which is the overlap of a deuteron in the ^{3}He nucleus in momentum space. This form factor is the coherent sum of a direct form factor $\hat{F}_D$ and an exchange form factor $\hat{F}_E$, the last one coming from the Pauli principle for the two neutrons in the intermediate state. This exchange term $\hat{F}_E$ plays en important role at backward angles for the pion. As a result the $pd \to t\pi^+$ cross section is written as :

$$\frac{d\sigma}{d\Omega} = \frac{q\, P_{eff}\, S_{\pi d}}{q_{eff}\, PS}\; \frac{E_\pi\, E_p\, E_d\, E_T}{E_\pi^{eff}\, E_d^{eff}\, (E_p^{eff})^2}\; \left| \hat{F}_D(Q) - \hat{F}_E(Q) \right|^2 \frac{d\sigma}{d\Omega}\,(pp \to d\pi)$$

where Q is the momentum transfer $Q = \left| \frac{1}{2}\vec{p} - \frac{1}{3}\vec{q} \right|$. (For the meaning of symbols see Ref. 8). The total c.m. energy $S^{1/2}$ of the $pd \to t\pi^+$ system is related to the total energy $S^{1/2}_{\pi d}$ of the subsystem $pp \to d\pi$ through

$$S = \frac{3}{2}\, S_{\pi d} + 3\, m^2 - \frac{1}{2}\, \mu^2,$$

which neglects the Fermi motion in the triton. We have slightly modified the kinematical factor appearing in the formula giving the cross section in Ref. 8, to take into account the recoil of the deuteron and the triton. This increases the cross section by an amount of 10 % at the highest energy ($T_p = 2.5$ GeV).

The result of this calculation is shown on Fig. 3 b in comparison with our experimental data. Two different wave functions have been used : the 3-poles wave function given by Locher and Weber (full line) with the same factor of 2 multiplying the exchange form factor $\hat{F}_E$ as given in their work and an Eckart type wave function (Ref. 9)

$$\psi(r) = \frac{N}{r} e^{-\alpha r}(1 - e^{-\beta r}),$$

with $\alpha = 0.42\ \text{fm}^{-1}$ and $\beta = 1.8\ \text{fm}^{-1}$ (Ref. 10) (dashed line). The two curves correspond to $pd \rightarrow t\pi^+$, so they have to be renormalized by a factor 2 when compared to the experimental data, due to isospin conservation. The elementary interaction $pp \rightarrow d\pi^+$ needed in this calculation is obtained fitting the experimental data available at $\theta_\pi = 180°$ (Ref. 11) and is shown on Fig. 3a. One can see that this calculation misses completely the large bump observed at $T_p = 1.2$ GeV and that the calculated cross section is quite below the experimental result in this energy region by at least a factor of one hundred.

ii) - The model of Barry (Ref. 12) where the $pd \rightarrow t\pi$ reaction is related to the $\pi d \rightarrow d\pi$ reaction when the pions are backscattered :

$$\frac{d\sigma}{d\Omega_\theta}(pd \rightarrow t\pi) = \frac{1}{2} G^2{}_{pt}(k_i^2) \frac{|t_\pi|}{|p_d|} \frac{S_{\pi d}}{S_{\pi t}} \frac{d\sigma}{d\Omega_\delta}(\pi d \rightarrow d\pi)$$

with the same notation as used in the Ref. 12.

This calculation is shown on Fig. 4 b with the angular correspondance $\cos\theta = \cos\delta = -1$. The calculation is normalized to give the experimental value at $T_p = 0.9$ GeV. Since the publication by Barry, new valuable backward $\pi^+ d$ elastic scattering have been measured (Ref. 13) and are shown on Fig. 4 a. The fit of the data appearing in this figure (dashed line) has been used as the elementary interaction in our calculation shown on Fig. 4 b.

The general trend is well reproduced except that the large structure at $T_p = 1.2$ GeV is not well accounted for. The small structure appearing in the calculation at the right place which is not able to reproduce the experimental observation is due to the small structure in the $\pi d \to d\pi$ around $T_\pi = 0.6$ GeV. The rescattering of the pion in the final state of the $pd \to \tau\pi$ could enlarge and broaden the calculated structure.

V - DISCUSSION

In the previous part, the interpretation of the $pd \to \tau\pi^\circ$ excitation function at 180° in terms of $pp \to d\pi$, even with an exchange term is unable to yield a large structure as observed. Moreover, the calculation is very sensitive to the very high momentum component of the wave function, which is unknown. The two wave functions used give the limits between which a realistic wave function must lie for small distances.

The model in terms of $\pi d \to d\pi$ seems to reproduce the main trend of the excitation function even if the bump is not well accounted for. This relies over a few $\pi d \to \pi d$ elastic scattering data that should be more extensively measured. This model emphasizes the role of baryonic excitation in the intermediate state and washes out the momentum dependance of the ^3He wave function.

At this point of the discussion the question is to know if this large structure due to baryonic excitations implies a two or a three nucleon mechanism. The answer could be found studying the $pd \to \tau\eta^\circ$ excitation function drawn on Fig. 2 which also shows two well marked structures. Unfortunately the OPE model of G.W. Barry cannot be used because of the isospin violation of the $\pi d \to d\eta^\circ$ reaction which would be the elementary interaction entering in this model.

The presentation of the results as a function of $w = W - 2\,M_N$ on Fig. 2 shows up the excitation of nucleon resonances at the total c.m. energy $W = 2\,M_N + M_{N^*}$ where M_{N^*} is the mass of nucleon resonance involved.

These masses are shown on the upper part of the Fig. 2. Only the Δ and N^* having 3 or 4 stars status from the last Review of the Particle Data Groups (Ref. 14) are shown, except the $N^*(1990)$ which has 2 stars. It is very interesting to point out the remarkable correspondances existing :

- in the pd → $T\pi^\circ$ between the two structures observed and the Δ(1232) for the first one and the $N^*(1650)$ and $N^*(1680)$ for the second one. These N^* are known (Ref. 13) to have a very large branching ratio in the $N\pi$ channel.

- in the pd → $T\eta^\circ$ between the two structures observed and the $N^*(1710)$ and $N^*(1720)$ for the first one and $N^*(1990)$ for the second one. These two N^* have large branching ratio in the $N\eta^\circ$ channel. The origine of the peaking of the cross section near the threshold could be found in the excitation of the $N^*(1440)$ which is below the threshold in this energy correspondance, but that has also a large branching ratio in the $N\eta^\circ$ channel. In that sense the $N^*(1535)$ having also an important $N\eta^\circ$ decay mode should produce a structure in this excitation function, except that contrary to the other N^* here involved, it has and odd parity.

VI - CONCLUSION

To conclude, one can say that the structures observed in the pd → $T\pi^\circ$ and pd → $T\eta^\circ$ excitation functions at $\theta_\pi = \theta_\eta = 180°$ seem to be related to the excitation of respectively Δ and N^* having large branching ratio either in $N\pi$ or $N\eta$ channels. For the pd → $t\pi$ reactions, the fact that here $N^*(I = \frac{1}{2}$ or $I = \frac{3}{2})$ can be excited in intermediate states through entrance channel with $I = \frac{1}{2}$, shows that isospin flip transitions occur in the deuteron excited by the incoming proton in a coherent process.

At present time, it is hard to conclude that a coherent participation of the three nucleons is forming a true three baryonic eigen state . The future experimental development must include a u - or cos θ - dependance of these two reactions at backward angles and should be extended to higher energies.

We greatly acknowledge the SATURNE Synchrotron crew and the Low Temperature Service of IPN for their kind cooperation.

TABLE I

pd → $t\pi$

T_{lab} (GeV)	θ_{lab}	$d\sigma/d\Omega$ lab. nb/sr	$d\sigma/d\Omega_{cm}$ nb/sr	Uncertainties	
				statistical	systematic
0.6	- 0.5	11.500	624	1.3 %	1.0 %
0.7	- 0.5	4.180	251	6.0 %	1.0 %
0.8	0	1.080	69.3	2.3 %	1.0 %
0.9	0	635	43.2	3.7 %	1.0 %
1.0	0	690	49	3.5 %	1.0 %
1.1	0	850	63	3.2 %	1.0 %
1.2	0	920	70	2.9 %	1.0 %
1.3	0	656	51.2	2.9 %	1.0 %
1.4	0	315	25.2	6.3 %	1.0 %
1.5	- 0.5	222	18.0	2.8 %	1.0 %

TABLE II

$p + d \rightarrow {}^{3}He + \pi^{\circ}$

T_p (GeV)	θ^{τ}_{lab}	$d\sigma/d\Omega_{lab}$ (nb/sr)	$d\sigma/d\Omega_{cm}$ (nb/sr)	Uncertainties	
				Statistical	Systematic
0.920 0.920	0 2	233 236	16.1 16.3	14 % 3 %	20 % 5 %
1.65	1	35.4	2.90	7 %	5 %
1.85	1	11.4	0.90	30 %	35 %
2.0	1	8.0	0.68	36 %	30 %
2.3	1	7.3	0.63	35 %	50 %

TABLE III

$p + d \rightarrow {}^3He + \eta^0$

T_p (GeV)	θ^T_{lab}	$d\sigma/d\Omega_{lab}$ (nb/sr)	$d\sigma/d\Omega_{cm}$ (nb/sr)	Uncertainties	
				Statistical	Systematic
0.920	0	234	14.6	1.3 %	10 %
	2	290	17.1	5 %	11 %
0.950	0	534	6.5	3.6 %	10 %
	2	705	8.3	2.3 %	10 %
	4	1030	10.9	7.5 %	10 %
0.975	0	156	3.8	10 %	20 %
1.000	0	147	3.0	8 %	30 %
	2	180	3.6	8.4 %	3 %
	4	291	5.6	5.4 %	13 %
	6	572	9.9	3 %	10 %
1.050	0	77	2.1	14 %	20 %
	2	99	2.6	8 %	20 %
	4	120	3.1	5.8 %	8 %
	6	262	6.4	5.5 %	2.5 %
1.149	0	56.5	2.1	14 %	20 %
	2	57	2.1	9 %	12 %
	3.86	65	2.4	14 %	20 %
	6	101	3.6	6 %	10 %
1.250	0	130	5.9	12 %	17 %
	1	102	4.6	15 %	1 %
	2	81	3.7	13 %	3 %
	4	53	2.4	20 %	25 %
	6	79	3.5	14 %	8 %

TABLE III (suite)

T_p (GeV)	θ^T_{lab}	$d\sigma/d\Omega_{lab}$ (nb/sr)	$d\sigma/d\Omega_{cm}$ (nb/sr)	Uncertainties	
				Statistical	Systemati
1.350	0	135	7.0	10 %	5 %
	1	126	6.5	8.8 %	4 %
	2	119	6.1	8.3 %	4 %
	3.86	85	4.35	5 %	3 %
	4	83	4.3	13 %	7 %
1.450	0	77	4.4	10 %	5 %
	2	58	3.3	10 %	5 %
	4	53	3.0	10 %	5 %
1.550	0	60	3.6	13 %	5 %
	4	47	2.8	8 %	10 %
1.650	0.5	37	2.4	12 %	5 %
	3.86	41	2.8	13 %	1 %
1.750	0	45	3.0	20 %	5 %
	4	42	2.8	9 %	1 %
1.850	1	41	2.9	10 %	5 %
2.000	1	25	1.8	9 %	4 %
	2	28	2.0	9 %	4 %

TABLE III (suite)

T_p (GeV)	θ^{τ}_{lab}	$d\sigma/d\Omega_{lab}$ (nb/sr)	$d\sigma/d\Omega_{cm}$ (nb/sr)	Uncertainties	
				Statistical	Systematic
2.150	1	13.5	1.0	19 %	15 %
	2	14.1	1.05	13 %	8 %
	3.86	13.1	0.98	12 %	8 %
2.300	1	13.2	1.0	33 %	10 %
	3	8.6	0.66	23 %	5 %
2.600	3	$\leq$ 2.8	$\leq$ 0.22		

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TABLE CAPTION

Table I - Cross sections of the $pd \to t\pi^+$ reaction. The systematic uncertainty is obtained as a result of the difference between the upper and the lower background that can be extracted below the peak.

Table II - Cross sections of the $pd \to T\pi^0$ reaction.

Table III - Cross sections of the $pd \to T\eta^0$ reaction.

FIGURE CAPTION

Fig. 1 – Experimental spectra showing what is observed in the focal plane of the SPES 4 spectrometer (Fig. 1a) and obtained after software analysis (Fig. 1b).

Fig. 2 – The $\theta_\pi = \theta_\eta = 180°$ excitation functions of the $pd \to \tau\pi^\circ$ and $pd \to \tau\eta^\circ$ reactions as a function of the total c.m. energy minus two nucleon masses. The value quoted (a) is an upper value of the cross section $pd \to \tau\eta^\circ$ at $T_p = 2.6$ GeV. The baryonic excitation masses shown in the upper part of the figure are taken from Ref. 14.

Fig. 3 – Comparison between the experimental data and the calculation in the model of Barry for the $\theta_\pi = 180°$ excitation function of the $pd \to \tau\pi^\circ$ reaction

<u>Fig. 3a</u> : the $\pi d \to d\pi$ elementary interaction (dashed curve) fitted on the data of Ref. 13 and used in the calculation.

<u>Fig. 3b</u> : the result of the calculation (full line curve) in comparison of the data, as a function of the kinetic proton energy.

Fig. 4 - Comparison between the experimental data and the calculation in the model of Locher and Weber for the $\theta_\pi = 180°$ excitation function of the $pd \rightarrow \tau\pi^0$ reaction :

<u>Fig. 4a</u> : the $pp \rightarrow d\pi$ elementary interaction (dashed line) fitted on the data of Ref. 11 and used in the calculation

<u>Fig. 4b</u> : the result of the calculation using the 3-pole (full line curve) and the Eckart form (dashed line curve) wave functions in comparison with the data, as a function on the kinetic proton energy. The upper scale shows the correspondance with the momentum transfer Q.

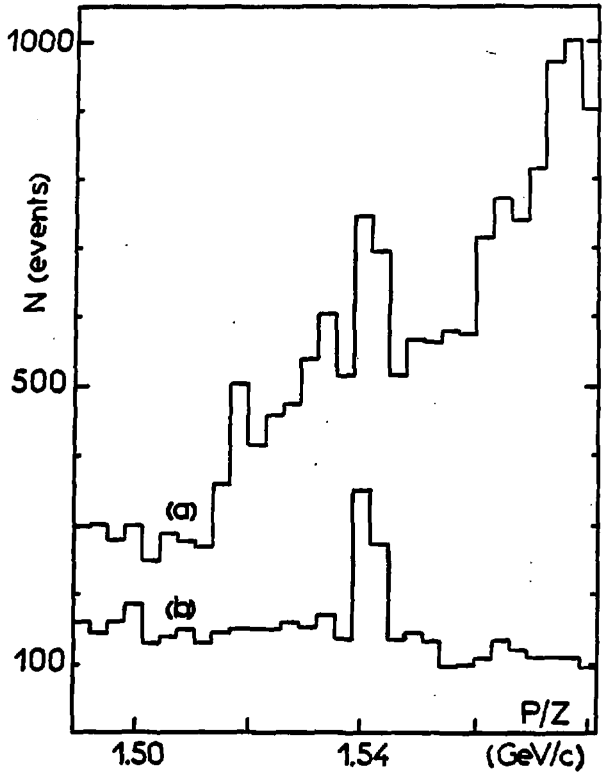
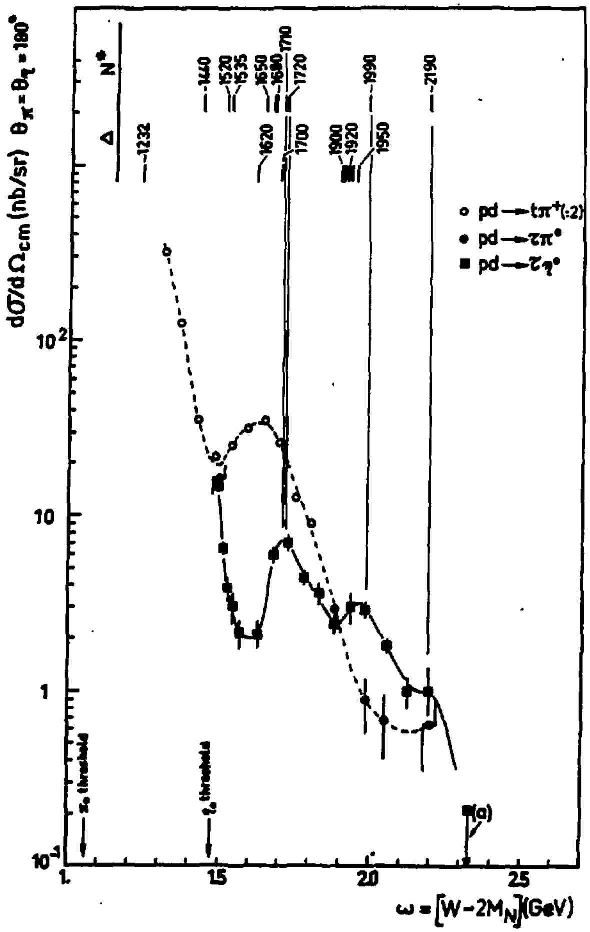


Fig. 1


dσ/dΩcm (nb/sr) θπ = θη = 180°
Δ
N*
1232
1440
1520
1535
1650
1680
1710
1720
1620
1700
1900
1920
1950
1990
2190
○ pd → tπ⁺(:2)
● pd → τπ°
■ pd → τη°
π₀ threshold
η₀ threshold
(a)
10²
10
1
10⁻¹
1.
1.5
2.0
2.5
ω = [W − 2M_N](GeV)

Fg. 2

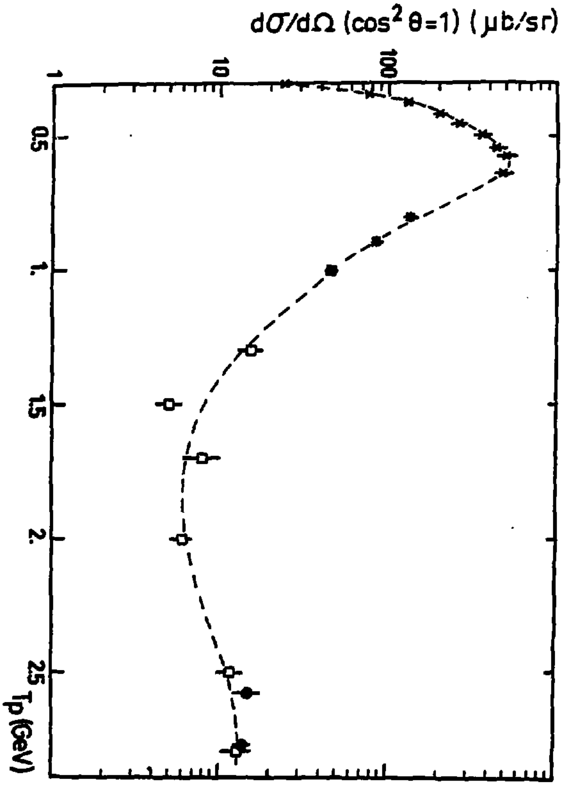


Fig 3a

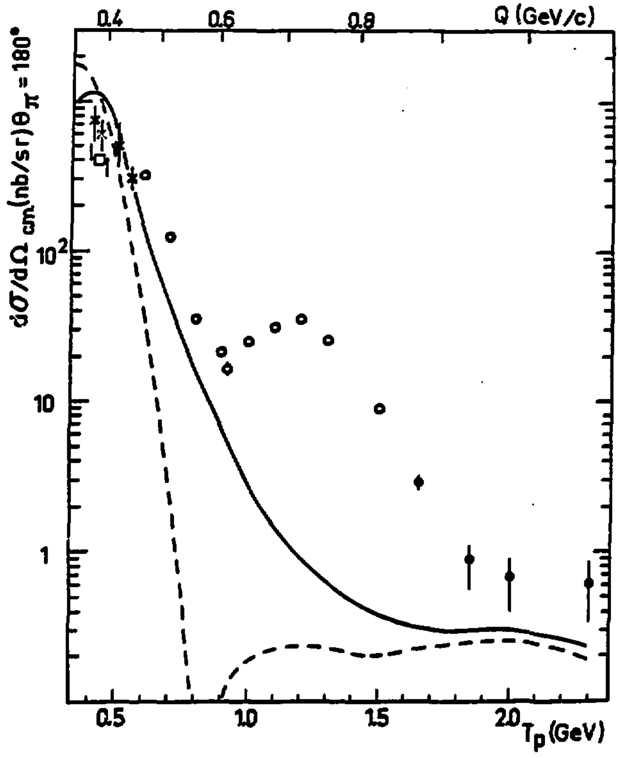


Fig. 3 b

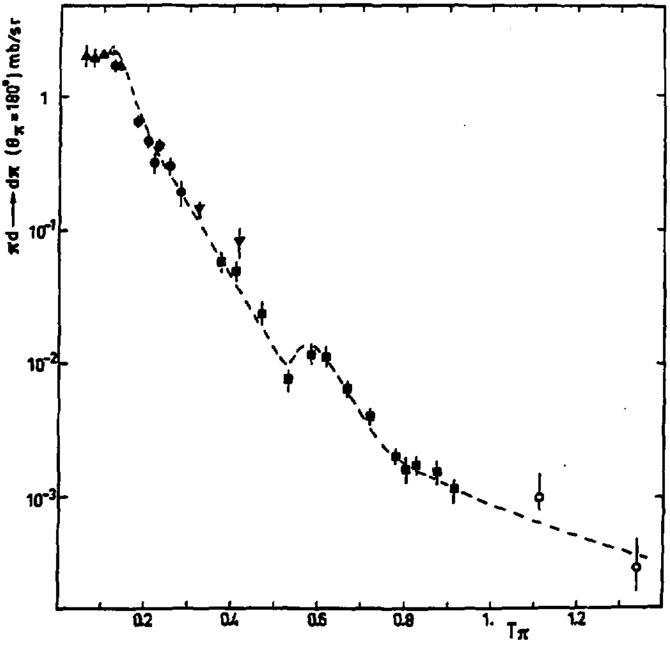


Fig. 4a

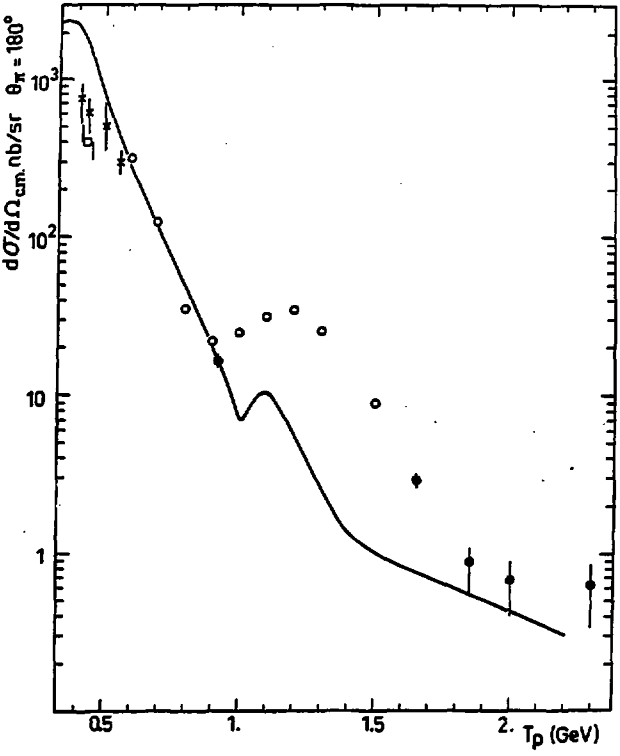


Fig 4b