COMPARISON OF NP AND DP INTERACTIONS WITH PION PRODUCTION AT 1.7 GeV/c PER NUCLEON

B. PASTIRČÁK, L.ŠÁNDOR

Institute of Experimental Physics, Slovak Academy of Sciences
Košice, Slovak Republic

A. DIRNER, G. MARTINSKÁ, J. URBÁN

University of P.J. Šafárik
Košice, Slovak Republic

J. HLAVÁČOVÁ

Technical University
Košice, Slovak Republic

V.V. GLAGOLEV, R.M. LEBEDEV, G.D. PESTOVA, S.S. SHIMANSKI,

A.P. JERUSALIMOV, V.N. PECHONOV, E.B. PLECHANOV, J.A. TROJAN

Joint Institute for Nuclear Research
Dubna, Russian Federative Republic

K.U. KHAIREDTINOV

Lebedev Physics Institute of Academy of Sciences
Moscow, Russian Federative Republic

A.K. KACHARAVA, M.S. NIORADZE, Z.R. SALUKVADZE

Tbilisi State University
Tbilisi, Georgian Republic

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Characteristics of reactions $dp \rightarrow ppp\pi^-$, $np \rightarrow pp\pi^-$, $dp \rightarrow dp\pi^+\pi^-$, $np \rightarrow d\pi^+\pi^-$, $dp \rightarrow dn\pi^+$ at 1.7 GeV/c per nucleon have been studied. By comparison of dp and np interactions the different mechanisms in deuteron reactions were separated and it was shown that the quasi free nucleon-proton process is dominant. More unambiguous selection of spectators was demonstrated simultaneously. Their momenta distributions were well described by the known deuteron wave functions up to 0.4 GeV/c. It was shown that exotic effects at high momenta contribute in less than 3% of events.

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1. Introduction

The deuteron as the simplest and loosely bound nuclear system is of particular importance for the understanding of nuclear phenomena. One of the questions, which is intensively investigated, is its structure at small distances (< 1 fm) or at large internal momenta ($k > 0.2$ GeV/c), where the nucleons overlap and one can hope, that quark degrees of freedom will reveal themselves. The most precise experiments devoted to this problem are inclusive and exclusive measurements of inelastic *ed* scattering [1]. Their results fully agree within the experimental errors with inclusive proton spectra measurements from the fragmentation of deuterons on protons and nuclei at different beam momenta up to 9.1 GeV/c [2] and with the results from deuteron breakup by protons studying in exclusive approach [3]. An enhancement of the data over the predictions from the conventional deuteron wave functions $\psi(k)$ for momenta above 0.2 GeV/c was observed in all these experiments. This effect was interpreted as a peculiarity of the deuteron wave function (DWF) caused maybe by 6-quark state [4]. But nowadays it seems more likely to be a consequence of contributions to the reaction mechanism apart from quasi free scattering, which are not described by the impulse approximation (IA) . Such mechanisms as virtual pion absorption by a nucleon pair [6], its rescattering [5], isobar degrees of freedom excitation [8] and also relativistic effects [9] have been suggested. It was shown in exclusive measurements of dp and ^{4}Hep interactions, that in the channels without pions namely the π exchange processes have a great influence in the region of internal momenta 0.2 GeV/c $< k <$ 0.4 GeV/c [7].

We have investigated in our study the dp reactions with pions in the final state to diminish this contribution, owing to real pion emission. Furthermore, we could compare our data from *dp* interactions the analogical *np* interactions obtained in the same experimental conditions at the same energy per nucleon and performed by the same methodic. The comparison allows to separate the quasi free *np* process in *dp* interactions from more complicated nuclear ones possible only on the whole deuteron. In such a way we could also more unambiguously select the spectators and compare them with the known DWF's. However, the quasi free *np* interaction on the contrary to the elementary one is complicated by the off-mass-shell properties of the bound nucleons and by their Fermi motion. We have taken this into account and attempted to estimate its influence.

On the other hand we could distinguish, which mechanisms cause the pion production in dp interactions, on the contrary to the elementary np ones. This question is interesting, namely in reaction channels, where deuteron in the final state appears. In such elementary np reaction the deuteron can be formed by simple np clustering or by the intermediate $pp \to d\pi^+$ process [11]. In the case of *dp* reaction also the coherent pion production on a deuteron as being that in which the outgoing deuteron remains unbroken is possible [12].

2. Experimental characteristics of reactions

We have compared the

$$np \to pp\pi^- \qquad \text{(N1)}$$
$$np \to d\pi^+\pi^- \qquad \text{(N2)}$$

reactions from np experiment [10] with corresponding:

$$dp \to ppp\pi^- \qquad \text{(D1)}$$
$$dp \to dp\pi^+\pi^- \qquad \text{(D2)}$$

reactions from dp experiment. Simultaneously the reaction

$$dp \to dn\pi^+ \qquad \text{(D3)}$$

has been analyzed, because its final products features are similar to those in reaction (D2). The data were obtained by irradiation of the JINR 1-m hydrogen bubble chamber by a deuteron beam at 3.34 ± 0.08 GeV/c and a neutron beam at 1.73 ± 0.05 GeV/c, respectively. For convenience in comparison with other experiments and to obtain the information about the motion inside the deuteron in more straightforward way we will use the deuteron rest frame (DRF) instead of laboratory one in dp experiment analysis. The momentum of ingoing proton in this frame is 1.67 GeV/c. The samples fitting above refered reactions were collected from 6800 three prong *np* interaction and 4200 four prong *dp* interaction events with following total cross sections:

- $\sigma(np \to pp\pi^-) = 2.24 \pm 0.15$ mb
- $\sigma(np \to d\pi^+\pi^-) = 2.92 \pm 0.20$ mb
- $\sigma(dp \to ppp\pi^-) = 0.27 \pm 0.15$ mb
- $\sigma(dp \to dp\pi^+\pi^-) = 0.28 \pm 0.24$ mb
- $\sigma(dp \to dn\pi^+) = 1.32 \pm 0.22$ mb

The compared reactions (N1)–(D1) and (N2)–(D2) were kinematically fully determined and all events were identified unambiguously. Experimental conditions (4π-geometry) enabled to obtain the data without significant losses. We have estimated them to avoid the systematic errors in comparison. Analyzing the anisotropy in azimuthal distributions of slow particles in events with small squared momentum transfers we have found the losses less than 1% and the same in all reactions, so they impose no influence on their comparison.

We compared at first the statistically richest reactions (N1) and (D1).

3. The $dp \to ppp\pi^-$ and $np \to pp\pi^-$ reactions

One may assume, due to small deuteron binding energy, that most of the dp interactions proceed on neutron bound in the deuteron, while the remaining proton does not participate in the interaction. Such a process of quasi free $np \to pp\pi^-$ reaction can be described by the IA [13] (Fig. 1(a)). Among the three outgoing protons in the final state of reaction (D1) we assigned in the first approximation, following the usual definition, proton spectator p_s as the slowest one in the DRF. The two remaining protons we regarded as quasi free np interaction products.

The data from both (N1) and (D1) reactions were compared in *np* centre of mass system (CMS). Transformation to this system for a *dp* interaction was performed in the spirit of the IA by assumption, that the proton spectator is on its mass shell even before the interaction between neutron and proton-target takes place. In contrast, the neutron is considered to be a virtual and off its mass shell and we defined the energy-momentum four-vector associated with the bound neutron as:

$$K_n = (-\vec{k}_s, m_n - E_s)\,. \tag{1}$$

$\vec{k}_s, E_s$ is momentum vector and energy of proton p_s and m_n is the rest mass of neutron. However, this transformation is ambiguous, because it depends on spectator determination. Nevertheless, the angular distributions in this CMS of protons and π^- from reaction (D1) are quite compatible with those from reaction (N1). The obtained asymmetries ϵ_p and ϵ_π, presented in the

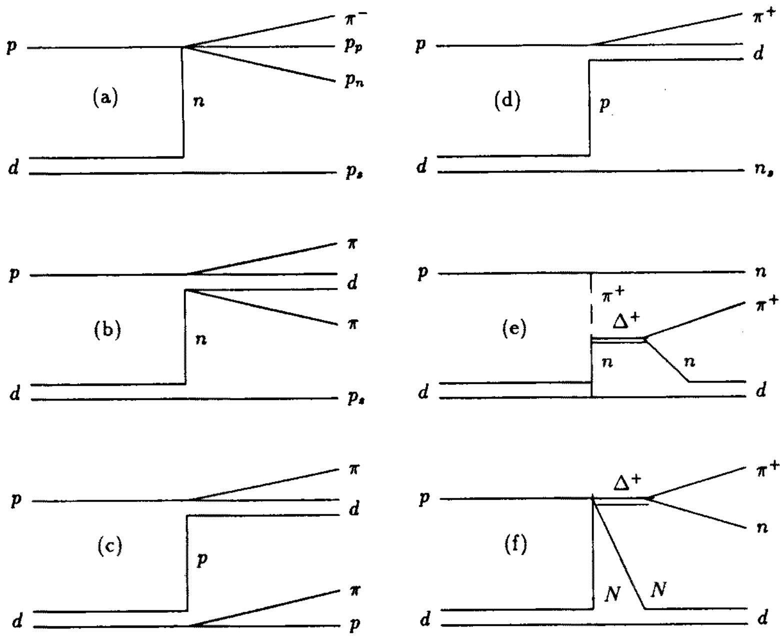

Fig. 1. Feynman diagrams of the processes discussed in the text.

Table I testify to compatibility of these distributions. The asymmetry here is defined as:

$$\epsilon = \frac{F - B}{F + B}, \tag{2}$$

where F and B are the numbers of particles outgoing into the forward and backward hemisphere, respectively. Indexes p, π stand for the protons and pions, respectively. Pions tend to forward emission and protons are concentrated around the forward-backward direction with a small asymmetry. Thus the basic characteristics, as the peripherality and pion emission of these reactions correspond in the first approximation. Owing to a significant peripherality of both processes we could associate each of the secondary protons with the corresponding initial nucleon. The relevance of a final state proton to the neutron (p_n) and proton (p_p) vertex, respectively, was determined by the procedure of minimal squared momentum transfer from initial to final nucleon. Pion can be at the same time produced in proton and in neutron vertex.

TABLE I

The asymmetries in angular distributions of protons and pions in np CMS from reactions $dp \rightarrow ppp\pi^-$ and $np \rightarrow pp\pi^-$

reaction	ϵ_p	ϵ_π
(D1)	0.052 ± 0.018	0.068 ± 0.018
(N1)	0.058 ± 0.012	0.076 ± 0.012

On the contrary to the angular distributions, the proton and pion momenta distributions from (N1) and (D1) reactions, respectively, considerably differ in details. It is natural to assume it as Fermi motion influence, because the momentum kinematical limit depends on the total energy of np collision $\sqrt{s}$. It varies with Fermi motion according to:

$$s = s_n - 2W(E_p + m_n) + W^2 - 2T_f(E_p + m_d) + 2\vec{k}_p\vec{k}_f\,, \tag{3}$$

where $\vec{k}_f$, T_f is the momentum vector and kinetic energy of Fermi motion; $\vec{k}_p$, E_p is the momentum vector and energy of ingoing proton; m_d, W is deuteron mass and binding energy and s_n is squared total energy of free np collision. Considering only this influence, we have estimated upper the Fermi momentum, which could be still registrable by our statistics:

$k_{\mathrm{max}} = 0.56 \pm 0.10$ GeV/c.

To get more refine coincidence between elementary and quasi free np interaction we have to define spectator in dp interaction more unambiguously. The customarily used spectator definition as the slowest nucleon in nucleus rest frame is partially artificial and has the physical sense only in the cases, when spectator is rather slower than other nucleons. Two main factors limits the exact spectator determination. The first one is the overlap between high momentum part of spectator distribution and low momentum part of struck protons spectrum, following from the fact, that struck protons are in some configurations slower than spectators. Processes, when both nucleons from deuteron interact (rescattering, final state interaction) are the second factor. We could reduce the mixing up taking into account the difference in angular distributions of spectators and the other protons. The spectator angular distribution is predicted in IA by the formula [12]:

$$\frac{dN}{d\cos\theta_s} = \int k_s^2|\psi(k_s)|^2\sigma(s)F(K_s, K_i)dk_s\,, \tag{4}$$

where $\psi(k_s)$ is the deuteron wave function, $\sigma(s)$ is the energy-dependent cross section for the corresponding neutron-proton reaction,

$$F = (K_s \cdot K_i - m_s m_i)^2$$

is invariant flux-factor and K_s, K_i are the four-momenta and m_s, m_i the masses of proton p_s and ingoing proton. The distribution deviates from isotropy due to flux-factor and energy dependence of cross section $\sigma(s)$ of reaction $np \to pp\pi^-$, which is in the region of our energy rather important (see Fig. 9). The influence of both these factors will be discussed later. Nevertheless, the spectators can be emitted into the whole space, on the contrary to the struck protons from quasi free np interaction, because they are kinematicaly constrained by the limiting angle $\theta_{\max} = 70°$. We chose a sample of events with the slowest proton p_s emitted into the angle:

$$\theta_s > \theta_{\max} . \tag{5}$$

The overlap of spectators and the struck protons in momentum distribution vanished after applying this cut. Correctness of such separation can be demonstrated by the comparison of spiral azimuthal distributions from elementary np interaction and those obtained from the dp interaction. The spiral coordinate system is defined for 3-particle final states and we can unambiguously calculate the spiral azimuthal angle in reaction (N1) as:

$$\lambda_{n,p} = \arccos \frac{(\vec{k}_{n,p} \times \vec{k}_a) \cdot (\vec{k}_{n,p} \times \vec{k}_\pi)}{|\vec{k}_{n,p} \times k_a| \cdot |\vec{k}_{n,p} \times \vec{k}_\pi|} \tag{6}$$

in the rest frame of (p_p, p_π), resp. (p_n, p_π) pair. Here $\vec{k}_a, \vec{k}_p, \vec{k}_n, \vec{k}_\pi$ denote the momenta of ingoing proton, secondary protons from neutron and proton vertices, respectively and of π^- in corresponding frame. We averaged over both vertices, because we do not know event by event in which one the pion was produced. The azimuthal distribution is symmetric with regard to 180° and we present it in interval (0°, 180°). The definition of λ in (D1) reaction depends on spectator determination. We present the distribution for events from reaction (N1) in Fig. 2(a), while we do it for all events and for formerly described selected sample of events from reaction (D1) in Fig. 2(b)–(c). The absence of bumps at 30° and 150° in distribution of all $dp \to ppp\pi^-$ events vanished in the case of selected sample and we reached the compatibility with $np \to pp\pi^-$ events. We can assume, that it is owing to correct selection of quasi free $np \to pp\pi^-$ process from (D1) reaction in the second case. The slowest protons from the selected sample of events are then real spectators and IA is valid in this case.

The measured spectator momentum distribution can be in IA directly related to the momentum distribution inside the deuteron, *i.e.* to the DWF in momentum space $\psi(k_s)$ by a simple relation:

$$\frac{dN}{dk_s} = \int k_s^2 |\psi(k_s)|^2 d\Omega . \tag{7}$$

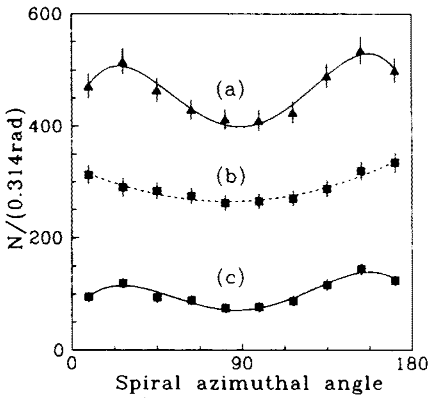

Fig. 2. Spiral azimuthal angle distributions from: (a) — all $np \rightarrow pp\pi^-$; (b) — all $dp \rightarrow ppp\pi^-$ events and (c) — $dp \rightarrow ppp\pi^-$ events satisfying the condition $\theta_s > \theta_{\max}$. The curves are polynomial fit results (solid — fourth order; dashed — second order).

It allows us to compare the obtained results with known DWF's among which we present here the Paris DWF [14], however the application of another DWF's and even the simplest Hulthen one yields practically the same result. The momenta distributions of the slowest protons p_s are presented in Fig. 3. They are drawn for all events from (D1) reaction and for the events cut by the condition (5). Full curve is the prediction obtained from the Paris DWF. One can see, that we have a good description of spectator momentum distribution behaviour for the selected sample of events even up to 0.4 GeV/c. To investigate the enhancement in high-momentum part of momentum spectra we have calculated the ratio of events, where the spectator momentum exceeds 0.2 GeV/c, to the events from the full distribution:

$$R = \frac{\int_{0.2}^{k_{\max}} \frac{dN}{dk_s} dk_s}{\int_{0.0}^{k_{\max}} \frac{dN}{dk_s} dk_s} 100\% \qquad (8)$$

for all (D1) reaction events, the selected sample (BW), for remaining events only (FW) and Paris DWF prediction. One can see from the results presented in the table 2 no remarkable excess of events above 0.2 GeV/c over the calculations for the sample satisfying the condition (5), unlike of considerable excess (8%) for conventionally defined spectator events, which is, however, more significant in pionless deuteron breakup reaction $dp \rightarrow ppn$ (12%) [7]. All above discussed facts imply, that the slowest protons emitted into angles greater than $\theta_{\max}$ in the $dp \rightarrow ppp\pi^-$ reaction at our energy are unambiguously spectators. For the other effects in high momentum part of spectra, such as virtual pion absorption, Δ isobar states excitation, 6-quark component, remains only about 1% of events.

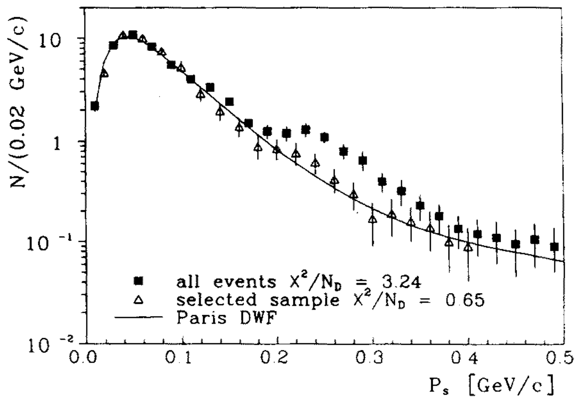

Fig. 3. Momenta distributions of the slowest protons p_s obtained for all events and for the selected sample (discussed in the text) from reaction $dp \to ppp\pi^-$ compared with Paris wave function.

TABLE II

The high momentum part of events in p_s protons momentum distribution from reaction $dp \to ppp\pi^-$.

R	All events	BW events	FW events	Paris DWF
%	16 ± 1	8.5 ± 0.5	23 ± 1.5	8

It can be also seen from the Table II, that there exists a large excess of observed events over the calculation for forward emitted protons p_s ($\theta_s < \theta_{max}$) with momenta greater than 0.2 GeV/c. There is no great difference between the momenta of all three final protons in this region and it was expected that they are the rescattering products. We have checked this assumption by analyzing the azimuthal correlations between all three proton pairs:

$$\phi_{jk} = \frac{\vec{k}_{jt} \cdot \vec{k}_{kt}}{|\vec{k}_{jt}| \cdot |\vec{k}_{kt}|}. \tag{9}$$

ϕ_{jk} is the relative azimuthal angle between the pair of secondary protons p_j and p_k calculated by using their transversal momenta $\vec{k}_{jt}, \vec{k}_{kt}$. We compared these azimuthal distributions in the following three regions:

- QBW: $\theta_s > \theta_{\max}$;
- QFW: $\theta_s < \theta_{\max}$ and $k_s < 0.2$ GeV/c;
- RSC: $\theta_s < \theta_{\max}$ and $k_s > 0.2$ GeV/c.

The corresponding asymmetries ϵ (F and B mean here the numbers of particle pairs with ϕ_{jk} less and greater then 90°, respectively) of these distributions are presented in Table III. The correlation is weak and of the same type between proton p_s and one of the remaining two protons, while is strong between protons p_p and p_n in the regions QBW and QFW. It testifies to applicability of IA in these regions. This picture rapidly changes in the region RSC. The correlation is now strong between all three proton pairs and above all arises between proton p_s and recoiled proton p_n. One may say, that this sample of spectatorless events is almost surely caused by rescattering.

TABLE III

Azimuthal correlations between proton pairs from reaction $dp \to ppp\pi^-$

proton pair	ϵ_{QBW}	ϵ_{QFW}	ϵ_{RSC}
p_n, p_p	0.73 ± 0.04	0.74 ± 0.04	0.62 ± 0.05
p_s, p_p	0.08 ± 0.03	0.07 ± 0.03	0.41 ± 0.06
p_s, p_n	0.14 ± 0.03	0.13 ± 0.03	0.36 ± 0.05

Taking into account these results we estimated

- the quasi free $np \to pp\pi^-$ cross section to be 2.11 ± 0.1 mb.

This value is in a good agreement with the energy dependence of the $np \to pp\pi^-$ reaction cross section, which is presented in Fig. 9.

4. The $dp \to dp\pi^+\pi^-, np \to d\pi^+\pi^-$ and $dp \to dn\pi^+$ reactions

We found that events from reaction (D2) split clearly into two groups Fig. 4(a)–(b) on the basis of the invariant relative four-velocity b_{id} between the initial beam particle i and the final state deuteron d:

$$b_{id} = -\left(\frac{K_i}{m_i} - \frac{K_d}{m_d}\right)^2, \tag{10}$$

where K are the four-momenta and m the masses of particles. We used this invariant variable to compare characteristics from the (N2) reaction with those from the reactions (D2) and (D3) independently of the initial

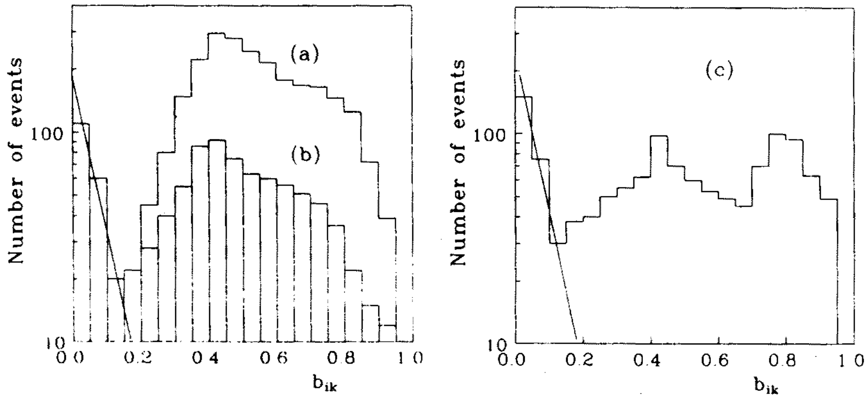

Fig. 4. **The distributions of the relative four-velocity b_{id} from reactions: (a) — $np \to d\pi^+\pi^-$; (b) — $dp \to dp\pi^+\pi^-$; (c) — $dp \to dn\pi^+$.**

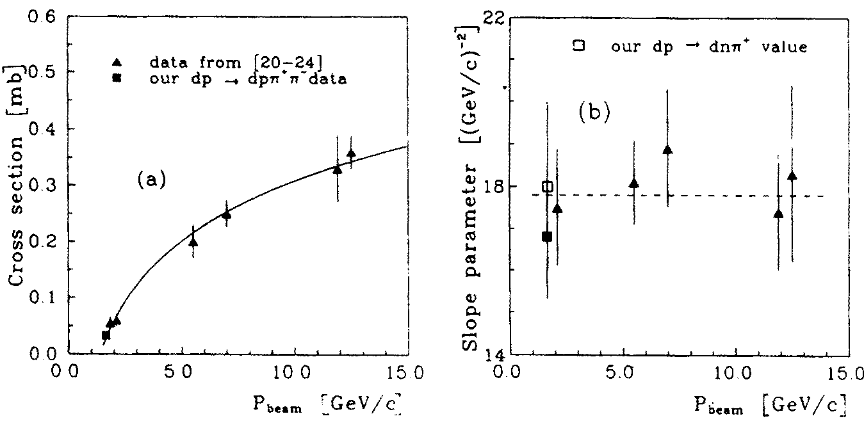

Fig. 5. **The $dp \to dp\pi^+\pi^-$ coherent production data from different *pd* experiments: (a) — the cross section dependence on proton beam momentum; the fit result is: $\sigma = 0.155 \ln(p_{beam} - 0.050)$; (b) — the slope parameters of differential cross sections $d\sigma/dt_{id}$.**

particles sort. On the contrary to the distribution obtained from (N2) reaction Fig. 4(a), there exists a cumulation of events at small b_{id} in reaction (D2) Fig. 4(b). Analogical cumulation could be also seen in b_{id} distribution obtained from reaction (D3) Fig. 4(c).

The subprocess which produces events in these cumulations is characterized by small momentum transfers between the incident and outgoing deuteron t_{id} ($t_{id} = m_d^2 b_{id}$), manifested by its rapid decreasing. We have treated these events as the coherent pion production on the deuteron with one pion exchange (OPE) mechanism and the elastic $\pi d \to \pi d$ scattering as the intermediate process [17]. The obtained slope parameters from differential cross sections $d\sigma/dt_{id}$ are nearly equal to the slopes from another hadron-deuteron experiments on coherent production at different incident momenta (hadron — $p, \bar{p}, K^{\pm}, \pi^{\pm}$). In Fig. 5(b) we compare our result with those obtained from pd experiments. Its cross section in (D2) reaction calculated by extrapolating the $d\sigma/dt_{id}$ is 0.043 ± 0.007 mb. The comparison with another coherent $dp \to dp\pi^+\pi^-$ reaction cross sections at higher energies is presented in Fig. 5(a). Our result is in agreement with permanent cross section increase with increasing proton beam momentum. It can be seen, however, that the coherent production is rather more probable at higher energies, its contribution in our case is not negligible. The sample of events available did not allow the investigation of the structures in invariant mass spectra.

The cross section of this OPE subprocess in reaction (D3) is 0.47 ± 0.07 mb, which is nearly equal to the result obtained at slightly higher (1.825 GeV/c) proton-beam momentum [16]. We observed a $d\pi^+$ enhancement for these events (Fig. 8). A three-body phase space with Breit–Wigner function fitted to this peak gives the position as:

- $M_{d\pi} = 2.185 \pm 0.020 \mathrm{GeV/c^2}$ at a width of $\Gamma = 0.155 \pm 0.035 \mathrm{GeV/c^2}$.

The proportion of events contributing to this peak within an $M_{d\pi}$ range of (2.03, 2.34) GeV/c^2 is $42 \pm 12\%$. The central value of $d\pi^+$ bump is approximately equal to the sum of $\Delta^+(1236)$ and a nucleon mass and the width is slightly wider than that obtained for Δ. The enhancement could be explained by a final state interaction of the exchanged π with one of the nucleons bound in the deuteron resulting in $\Delta^+(1236)$ formation. The Δ isobar than decays and the nucleon from its decay recombine with spectator to form the final state deuteron Fig. 1(e). It is due to resonant character of the elastic $\pi d \to \pi d$ scattering cross section at the energy near to sum of Δ and nucleon [18].

The squared momentum transfer t_{id} distribution of remaining events from (D2) reaction is flat enough and implies no contribution of the coherent production on the deuteron. In a peripheral model they must involve one nucleon exchange (ONE) as presented on most probable Feynman diagrams (Fig. 1(b)–(c)) [20]. We can consider the first subprocess as the quasi free $np \to d\pi^+\pi^-$ reaction proceeding on the neutron bound in deuteron and it corresponds to elementary $np \to d\pi^+\pi^-$. We compared at first all ONE events from (D2) reaction with those from reaction (N2) in np CMS according (1). Although the ONE events from reaction (D2) have to differ from elementary $np \to d\pi^+\pi^-$ reaction events due to influence of different ONE diagrams, this influence was not manifested in simple distributions, as momenta and angular distributions of deuterons and pions. The mean values $\bar{k}$, variances ϱ of deuteron and pions momenta presented in Table IV (in

GeV/c) do not differ in each case. The asymmetries in angular distributions were practically equal to zero in both cases.

TABLE IV

Mean values and variances of np CMS momenta distributions of deuterons and pions from reactions $dp \to dp\pi^+\pi^-$ and $np \to d\pi^+\pi^-$

reaction	$\bar{k}_d$	$\bar{k}_\pi$	ϱ_d	ϱ_π
(D2)	0.244	0.185	0.76	0.46
(N2)	0.240	0.178	0.70	0.44

To separate different ONE diagrams from (D2) reaction and thus obtain the contribution of quasi free np interaction and other processes possible only on deuteron we used the longitudinal phase space (LPS) analysis [19] simultaneously with comparison of reaction (N2) events. In the method of LPS analysis the phase space is divided into four sectors according to the $\pi^\pm$ mesons directions. Then we compared the events from different sectors with the events from $np \to d\pi^+\pi^-$ reaction. The central region, where the overlap of different processes is possible, was significantly less populated than the peripheral regions. The degree of division between the different processes was such, that the amount of events from process with both pions in the same vertex with deuteron (Fig. 1(b), and we denote them as the group A) was 80%, while the amount of events with π^+ resp. π^- in different vertices (Fig. 1(c), denoted as the group B) was 20%. The following differences between the A and B groups of events from reaction (D2) with regard to the (N2) reaction events were obtained:

- the A group events coincide with the deuteron momentum distribution of the events from reaction (N2), while the B group events are mostly out of this distribution;
- two significant peculiarities at 0.33 GeV/c^2 and 0.40 GeV/c^2 are present in the $M_{\pi\pi}$ invariant mass distributions for (N2) reaction events and for the A group events, while only one broad peak at 0.33 GeV/c^2 is present in $M_{\pi\pi}$ distribution for the B group events (Fig. 6);
- the maxima at 2.1 GeV/c^2 are present in both $M_{d\pi}$ invariant mass distributions for the reaction (N2) events and for the A group events, but no any enhancement could be seen in $M_{d\pi}$ distribution for the B group events (Fig. 7).

All these differences allow to assume, that the ONE events from the A group of reaction (D2) correspond to:

- quasi free $np \to d\pi^+\pi^-$ process with the cross section 0.19 ± 0.02 mb.

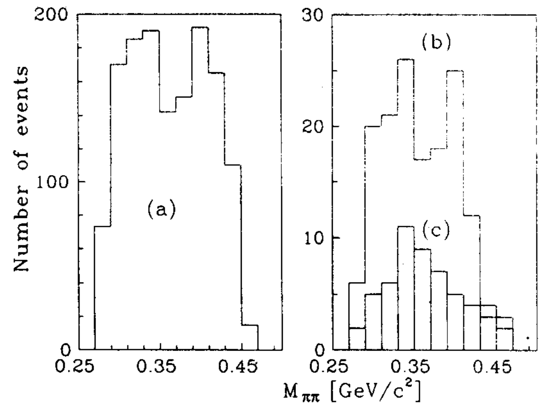

Fig. 6. Invariant $M_{\pi\pi}$ mass distributions: (a) — from $np \to d\pi^+\pi^-$ reaction events; (b) — for the group A events and (c) — for the group B events from reaction $dp \to dp\pi^+\pi^-$.

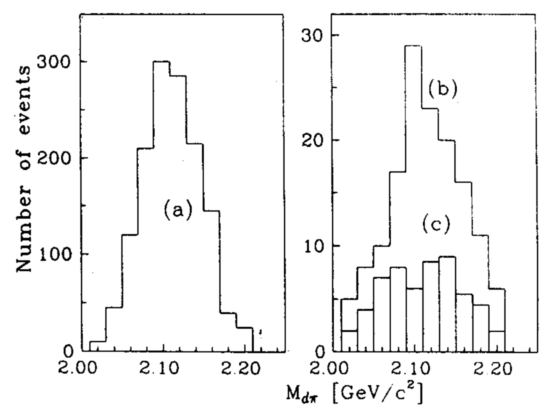

Fig. 7. Invariant $M_{d\pi}$ mass distributions: (a) — from $np \to d\pi^+\pi^-$ reaction events; (b) — for the group A events and (c) — for the group B events from reaction $dp \to dp\pi^+\pi^-$.

Similarly the events from reaction (D3), which come from clearly split fast deuteron bump (large b_{id} in Fig. 4(c)) were treated as ONE events with intermediate $pp \to d\pi^+$ as the basic reaction (Fig. 1(d)). We observed a significant maximum in the $M_{d\pi}$ spectrum for these events (Fig. 8). Fitting to this distribution, using combinations of Breit–Wigner function and phase space background, gives the proportion of events contributing to this maximum as $50 \pm 10\%$, with $\chi^2 = 53/44$,

- a mass of $2.315 \pm 0.010 GeV/c^2$ and a width of $\Gamma = 0.065 \pm 0.015$GeV/c^2.

The enhancement is 4 standard deviations over a fitted background. The

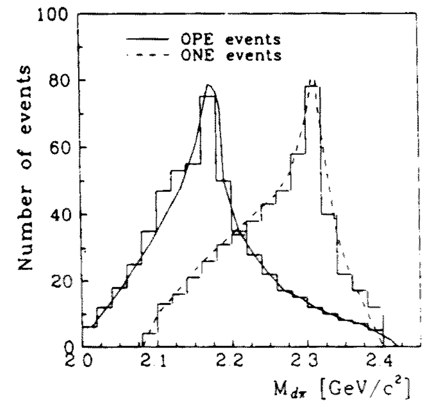

Fig. 8. Invariant $M_{d\pi}$ mass distributions for OPE and ONE deuteron events from reaction $dp \rightarrow dn\pi^+$. The curves are fit results obtained by using the combination of Breit–Wigner function and phase space background.

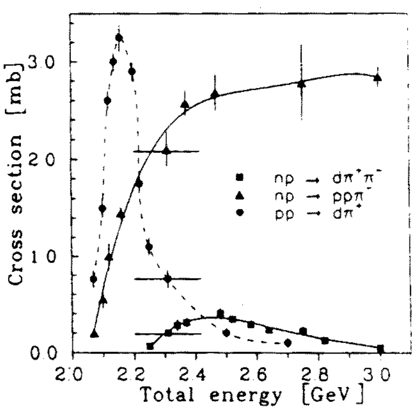

Fig. 9. The cross section energy dependencies of reactions: $np \rightarrow pp\pi^-$, $pp \rightarrow d\pi^+$, $np \rightarrow d\pi^+\pi^-$. The curves are polynomial fit results. Data were taken from [26] and for the reaction $np \rightarrow d\pi^+\pi^-$ also from [10]. Our quasi free pN values are assigned with the spread in total energy.

peak position is close to our total energy of pp collision ($\sqrt{s} = 2.312$ GeV) and such a behaviour of $M_{d\pi}$ distribution reflects the fact, that $d\pi^+$ pair comes from quasi free $pp \rightarrow d\pi^+$ reaction. The width of the peak is connected with the Fermi motion of nucleons bound in deuteron.

The last group of events from the reaction (D3), which contribute to the medium bump in Fig. 4(c) is characterized by a significant Δ production. The phase space background accounts for less than 40% of the events in $M_{n\pi}$ invariant mass distribution. The reaction mechanism with intermediate $pN \rightarrow N\Delta^+$ process seems to be dominant in this case [15] (Fig. 1(f)). The energy distribution of π^+ follows fairly well the resonance character of

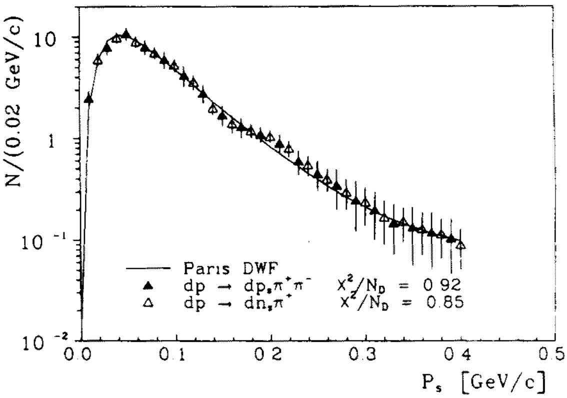

Fig. 10. Momenta distributions of spectators from quasi free pN processes in reactions: $dp \to dp_s\pi^+\pi^-$ and $dp \to dn_s\pi^+$ are compared with Paris wave function.

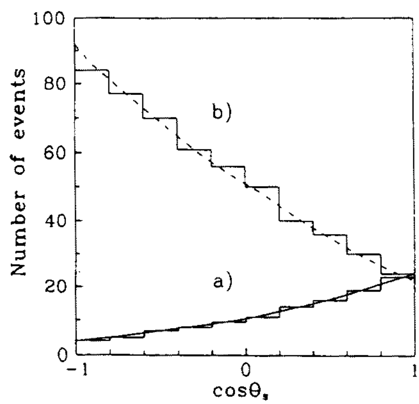

Fig. 11. The nucleon spectator angular distributions from reactions: (a) — $dp \to dp_s\pi^+\pi^-$ and (b) — $dp \to dn_s\pi^+$. The curves are the results following from formula (3).

$NN \to N\Delta \to NN\pi$ reaction with maximum at 0.1 GeV/c [25]. However, the evidence of some enhancement in $M_{d\pi}$ distribution at 2.3 GeV/c^2 for these events imply the admixture of events from previous case. Analyzing $M_{n\pi}$ and $M_{d\pi}$ invariant mass spectra we estimated the cross sections of both subprocesses to be:

- 0.82 ± 0.15 mb for quasi free $pp \to d\pi^+$ subprocess and
- 0.17 ± 0.06 mb for intermediate $pN \to N\Delta^+$ subprocess.

The above determined total cross sections of quasi free $np \to d\pi^+\pi^-$ and $pp \to d\pi^+$ reactions enter well into the energy dependencies of cross sections of these reactions on free nucleons, similarly as in the quasi free $np \to pp\pi^-$ case. The energy dependencies are presented in Fig. 9. We can furthermore say that the ONE in reactions (D2) and (D3) proceed dominantly through the quasi free $np \to d\pi^+\pi^-$ and $pp \to d\pi^+$ processes, but in reaction (D3) also the Δ production in $pN \to N\Delta^+$ is quite significant.

The protons in reaction (D2) and the neutrons in reaction (D3), respectively, are spectators in above selected quasi free np resp. *pp* processes. Their momenta distributions (Fig. 10) are well described by the Paris DWF up to 0.4 GeV/c. The excess of the observed values over the calculated ones in the high momentum region according to (8) was in both cases less than 3%.

Their angular distributions (Fig. 11) could be well described according the formula (4), when the influence of flux-factor and the $\sigma(s)$ dependencies (from Fig. 9) were taken into account. The energy spread because of Fermi motion is $\Delta s = 4k_p k_{\max}$. The opposite inclines of angular distributions are due to different and strong $\sigma(s)$ dependencies, while the influence of the flux-factor has been found rather less important.

5. Summary

The reactions with one-pion and two-pion production from dp interactions were studied together with corresponding reactions from np interactions at 1.7 GeV/c/nucleon. They were obtained in the same experimental conditions, processed by the same methodic and compared with the following results:

- Besides the general qualitative agreement in corresponding np and dp reaction products characteristics there were observed differences, caused by nuclear effects and different reaction mechanisms.
- The comparison enabled to determine the contributions of quasi free nucleon-proton processes on nucleon bound in the deuteron. It was shown, that all three analysed dp reactions $dp \to ppp\pi^-$, $dp \to dp\pi^+\pi^-$ and $dp \to dn\pi^+$ proceed mainly like quasi free processes and their cross sections enter fairly well into energy dependencies of the cross sections $\sigma(s)$ of corresponding reactions proceeding on free nucleons.
- By selection of quasi free nucleon-proton scattering events the spectators were determined more unambiguously than by usual spectator definition as the slowest nucleon in DRF only. Their momenta distributions are well described by the Paris DWF up to 0.4 GeV/c. The angular distributions agree also with the prediction, when we take into account $\sigma(s)$ dependencies. The excess of observed values over the Paris DWF prediction in high momentum part for quasi free nucleon-proton interaction events, which is caused may be by exotic effects for these, does not exceed 3%. It is rather less than such excess for all events

from these channels, which is, however, less than this one in pionless channel.

- It was shown that the spectatorless events from reaction $dp \to ppp\pi^-$ are rescattering products.
- The comparison of reactions $dp \to dp\pi^+\pi^-$ and $np \to d\pi^+\pi^-$, simultaneously with the reaction $dp \to dn\pi^+$ analysis, enabled to separate different mechanisms of pion production and deuteron formation in dp reactions. The contribution of pion coherent production on deuteron was registered and observed to be small, but in the agreement with the data from other pd experiments.

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