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FEASIBILITY OF DEUTERON BREAK-UP STUDY AT COSY 0° FACILITY (ANKE)

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Introduction. The system of detectors of the ANKE setup under construction at the COSY accelerator (KFA, Jülich) is aimed to study a wide class of proton- nucleus reactions [1]. In the present paper the kinematic conditions of the deuteron break-up interaction with the COSY proton beam are considered. The physical motivation of this investigation and the scheme of the experiments are given in papers [2],[3]. The aim of the present paper is to estimate the efficiency of the system of detectors in registration of different channels of proton-deuteron interaction, the background level and the possibility of identifying the events of the deuteron break-up $pd \rightarrow ppn$.

Our calculations are based on the experimental data obtained with a 1-meter hydrogen bubble chamber of the Laboratory of High Energies at JINR [7] bombarded with a deuteron beam of 3.3 GeV/c momentum, which corresponds to 1.7 GeV/c proton momentum in the deuteron rest frame (proton kinetic energy is $1.0\,GeV$). Using real events we can estimate physical background processes accompanying the break-up process and study the possibility of separation of the latter. Available experimental data might be useful for optimization of the experimental setup.

Physical Problem. A physical problem of this experiment is the exclusive study of the deuteron break-up by protons under kinematic conditions far from kinematics of quasi-free nucleon-nucleon interaction. For this purpose the "collinear geometry" of the experiment is chosen, when protons emmited at angles close to 0° and 180° are detected in coincidence. For protons scattered at 180° with momenta close to the kinematic limit, the conditions of cumulative process, i.e. emission of particles with momenta forbidden for free NN scattering, are fulfilled. In our case the cumulative process has a simple form, not complicated by additional factors: the simplest target nucleus involved, no particles produced, three particle final state allowing variation of kinematical variables in a wide range. Usage of polarized beams and targets at the second stage of the experiment will allow detailed information for the study of the mechanism of "elementary" cumulative process [2],[3], [4]. Nevertheless a systematic study of spin-averaged two-particle differential cross sections in the range of kinetic energies of incident proton $T_p = 1 \div 2.5 GeV$ seems to be a necessary and important step in this direction.

Experimental Setup. The experimental setup is shown in Fig.1. The main part of the setup is the achromatic system of three dipole magnets D1, D2, D3 arranged along the internal beam of the storage ring. Two of the magnets are used as spectrometric ones: D1 for backward ejectiles and D2 for forward ejectiles coming from the target placed in the accelerator internal beam between D1 and D2. The D2 gap restricting the acceptable phase space in the forward direction is equal to $20\,cm$. The strength of the equivalent homogenous magnetic field of D2 was taken to be $1.05\ T$. D1 and D3 are the same with a gap of $9\,cm$ and with the same magnetic field strengths.

For particle detection in the forward and backward directions the forward (FD) and backward (BD) detector systems will be used. The system of the forward detectors FD consists of three narrow-gap proportional chambers (MWPC) for measurement of momenta and emission angles of charged particles, two scintillation hodoscopes (S) and Čerenkov counters (Ch) of total internal reflection. The hodoscopes are identical and they have total dimensions equal to $68(W) \times 36(H)\,cm^2$. The backward detector system (BD) consists of three drift chambers (DC), two scintillation hodoscopes ($\Delta E_1, \Delta E_2$) and anticoincidence (VETO) counters placed behind the degrader. The backward hodoscopes cover the area of $50(W) \times 28(H)\,cm^2$. Each hodoscope consists of 8 scintillation counters. The thickness of the first plane counters equals to $0.5\,cm$ and for the second one $2.0\,cm$. A detailed description of the FD and BD systems can be found in papers [5],[6].

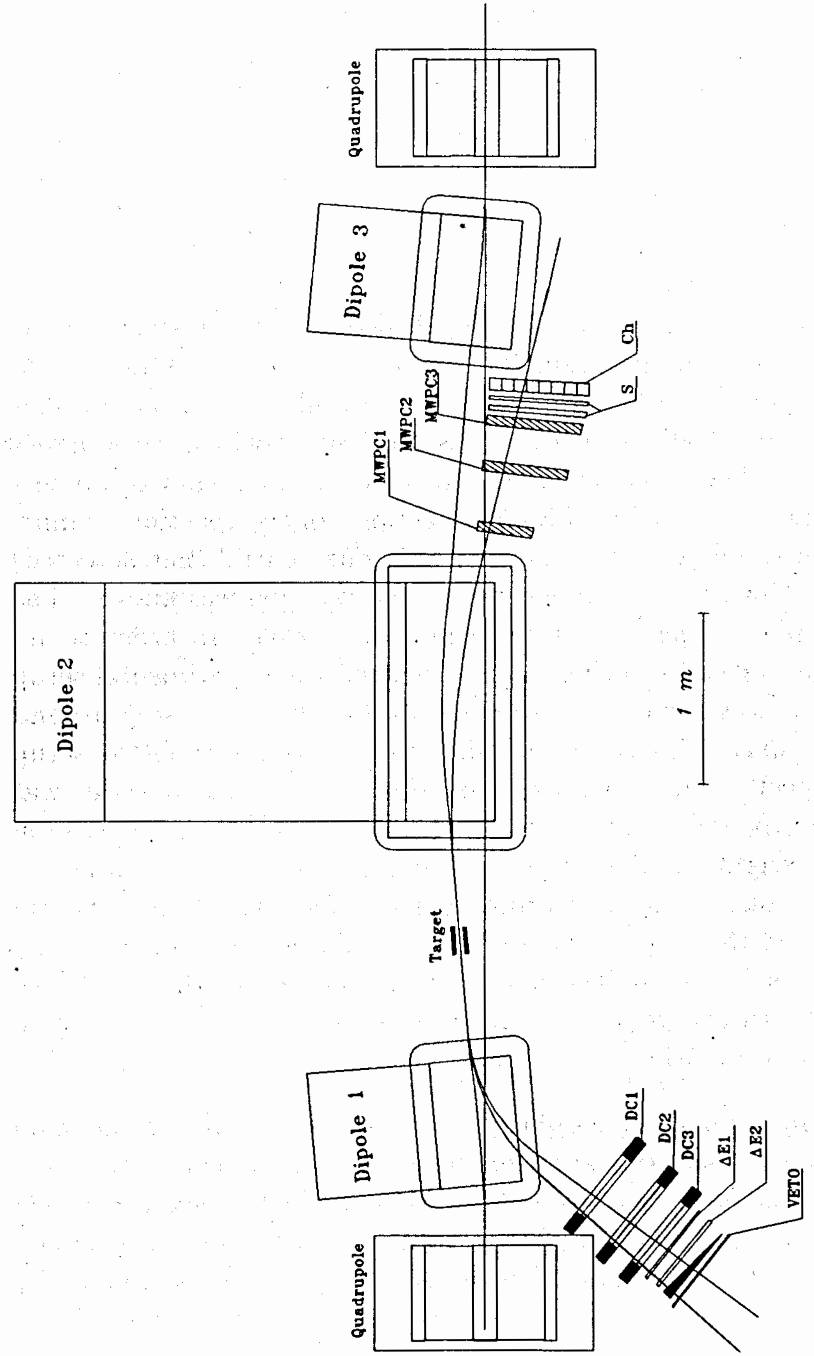

Fig.1. Scheme of the detectors arrangement for deuteron break-up study at ANKE.

Measurement Conditions. For description of the setup geometry, determination its characteristics, particle tracing and development of unified methods of data processing the program GEANT [8] was used. The events were generated on a point-like target placed in the internal beam of the accelerator, at a distance of 25 cm from D2. The direction of incident protons in the experimental events was aligned with the COSY beam direction. The real events of pd interaction obtained under 4π geometry conditions in the hydrogen bubble chamber with a 3.3 GeV/c deuteron beam were used as input events of the program (only a part of events of elastic scattering at small angles was lost). The available experimental material contained all reactions, cross sections of which were higher than $1\,mb$. The input event was a set of 4– momenta of all secondary particles produced in the reaction. In the reaction channel $pd \to ppn$ the final state contained only one neutral (not detected) particle. Thus, the full kinematics of the reaction was known. The total number of pd events was equal to 165000. In order to increase the statistics during tracing through the experimental setup each event was used 36 times with rotation by a 10° step around the beam axis. This can be justified by nonsymmetry of the setup with respect to the beam axis. By this method the statistics was increased up to 6 million events (with a corresponding decrease in statistic weights of the events). A particle was considered as detected if it passed all the coordinate detectors in the FD or BD arm and reached the second plane of the scintillation hodoscopes. Any interactions (electromagnetic as well as nuclear) of the secondary particles with components of the apparatus and air were neglected during the simulation.

Deuteron Break-up Reaction. It is well known [9] that the main type of reactions in the pd interactions is the mesonless break-up of the deuteron $pd \to ppn$, the cross section of which is equal to $37.2 \pm 1.4\,mb$ and amounts to 45% of the total pd interaction cross section $\sigma_{tot}(pd) = 82.89 \pm 0.06\,mb$. This class of events can be divided by

their mechanism into two groups: the direct break-up process (dir) and charge-exchange break-up process (cex). These groups differ by their kinematic characteristics. The selection criterion is a type of the fastest secondary particle. In the direct break-up it is a proton, in the charge-exchange reaction it is a neutron. The cross sections of these reactions (σ_i) are given in Table 1 the second column as well as the number of real events used in the simulation.

Table 1. Cross sections of different pd interaction channels [9], [12], [10], [11] and the corresponding input statistics at $1.7\,GeV/c$ momentum of proton beam ($T_p = 0.977\,GeV$). Rough estimation of previosly unpublished cross sections are marked by (*).

$pd \to \ldots$	σ_i, mb	σ_i/σ_{tot}, %	N_i
ppn(dir)	30.1±1.2	36.3	$63 \cdot 10^3$
ppn(cex)	6.4±0.2	7.7	$13 \cdot 10^3$
pd	12.2±0.4	14.5	$24 \cdot 10^3$
$pd\pi^0$	$\leq 1.0^*$		$3.2 \cdot 10^3$
$nd\pi^+$	1.32±0.22	1.6	$3.8 \cdot 10^3$
$ppn\pi^0$	11.2±0.4	13.5	$22 \cdot 10^3$
$pnn\pi^+$	17.0±0.6	20.5	$43 \cdot 10^3$
$ppp\pi^-$	2.2±0.2	2.7	$4 \cdot 10^3$
$pd\pi^+\pi^-$	0.276±0.024	0.3	$0.4 \cdot 10^3$
$ppn\pi^+\pi^-$	$< 1.0^*$		$2 \cdot 10^3$
$\pi^+\pi^+X$	$< 0.5^*$		$0.2 \cdot 10^3$

In Fig.2 the momentum distribution of both protons from the deuteron break-up events is presented. The shaded part of the histogram corresponds to the direct channel. Three peaks are observed, which can be qualitatively assigned to the following groups. The first one around 0.08 GeV/c corresponds to the so-called spectator protons, i.e. the particles which did not take part in interaction. The second ($\sim 0.4\,GeV/c$) and the third peaks ($\sim 1.6\,GeV/c$) correspond to protons which took part in interaction. The neutron

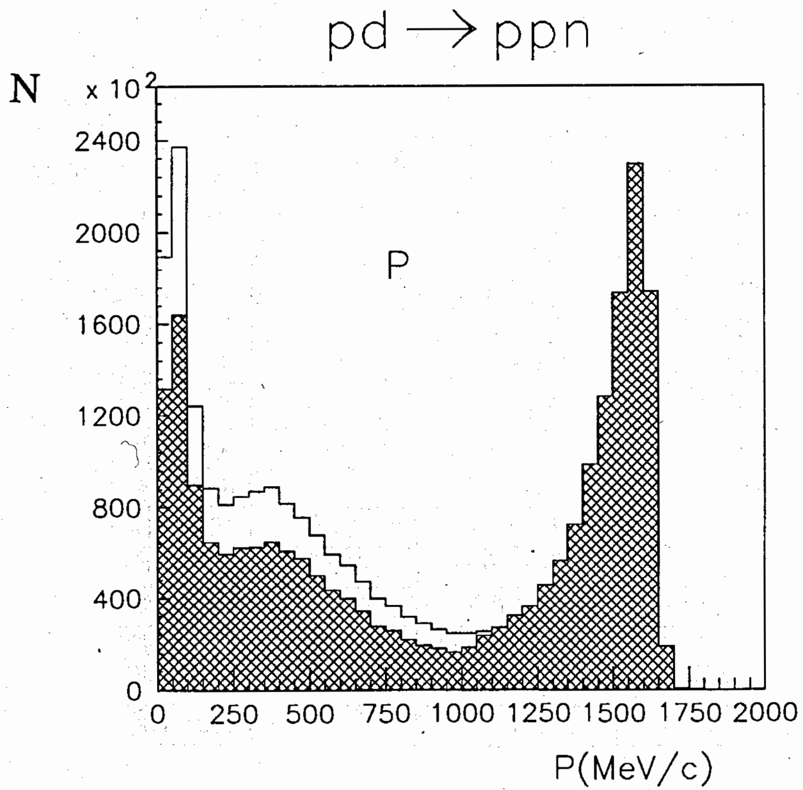

Fig.2. Momentum distribution of protons from the reaction $pd \to ppn$. The shaded part of the histogram corresponds to the direct channel.

spectrum has the same shape, which is not shown here. The momentum distribution of protons in the direct channel is shown by the shaded area. One can see that in the charge-exchange reaction the proton momenta do not exceed $1.0\,GeV/c$. Taking into consideration that the FD system is designed for detection of fast particles, we can assume that we shall mainly study the direct deuteron break-up. In fact, from the momentum spectrum of the fastest protons detected by the forward scintillation hodoscope (Fig.3a, shaded area) one can see that in the forward detector the fastest protons with average momentum of about $1.60 GeV/c$ will mainly be detected. The spectrum reflects the efficiency of detection of this channel. Hereafter, the shaded area corresponds to the 'detected' particles or events. The angular distribution of detected protons (shaded area) from all generated ones is given in Fig.3b.

Conditions for the study of the charge-exchange break-up is beyond scope of the present paper.

Background Processes. As was mentioned above, the cross section of the deuteron break-up amounts to almost a half of the total pd interaction cross section. The cross sections of all significant processes with charged secondaries (only detectable in the bubble chamber) in the final state are given in Table 1.

At the proton momentum of $1.7\,GeV/c$ the cross sections of the processes with production of two pions in NN collisions are small. Hence, the channels with production of one pion dominate among the final states with pions. As one can see from Table 1 the main background processes in the mesonless deuteron break-up are:

$$pd \to pd \tag{1}$$

$$pd \to p\pi^+(2n) \tag{2}$$

$$pd \to pp(n\pi^\circ) \tag{3}$$

The particles in brackets do not appear in the experimental data. However the reaction type is identified correctly. The reactions

$$pd \to dp\pi^+\pi^- \tag{4}$$

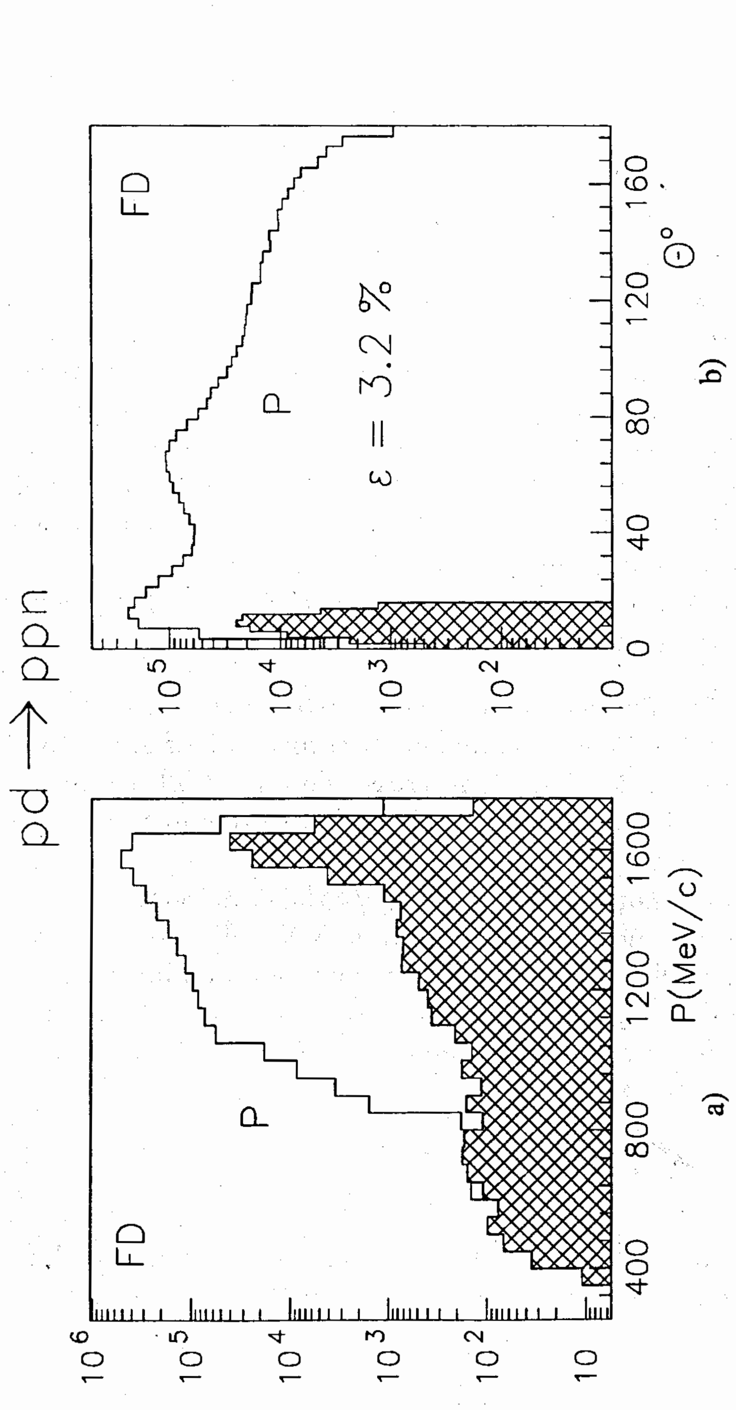

Fig.3. Momentum (a) and angular (b) distribution of fast protons from the reaction $pd \to ppn$. The shaded part of the histogram corresponds to the spectra of the protons that hit the forward scintillation hodoscope (FD).

$$pd \to ppn\pi^+\pi^- \quad (5)$$
$$pd \to dn\pi^+ \quad (6)$$
$$pd \to nnn\pi^+\pi^+ \quad (7)$$
$$pd \to ppp\pi^- \quad (8)$$

are excluded from consideration because their summary cross sections at the incident momentum of 1.7 GeV/c do not exceed 4 mb. Let us consider momentum and angular spectra of secondary particles in reactions (1,2,3) for particles generated in the available phase space and for detected ones as well.

(1) The elastic process $pd \to pd$ is the main background channel for counting in the forward detector, because the most part of protons from this reaction are scattered at small angles along the beam axis and therefore hit the forward detector. This can be seen from the momentum and angular distributions of protons in Figs. 4.a,b. The shaded parts of the spectra correspond to the protons that reached the FD detector. Their share amounts to 13% of all generated ones. For experimental procedure reasons a half of the elastic channel events (mainly at small angles) were lost at the bubble chamber data processing [13]. The lost events belong to the area of small momentum transfer (small angles). Thus, the above share of protons which reach the FD detector is underestimated approximately by a factor of two. This correction will be made below at the counting rate estimation for elastic channel.

The amount of deuterons which hit the forward detector is well below 1%, but these events are of interest for some reasons [14]. Deuterons at about 1.7 GeV/c can be separated from protons only by the threshold Čerenkov counter due to significant difference in their velocities.

(2) This reaction channel has the largest cross section ($17.0 \pm 0.6\,mb$) among the background processes. It also will be the main background channel with respect to the mesonless deuteron break-up. The momentum and angular spectra of protons and pions in this reaction are presented in Figs. 5.a-d respectively. In these

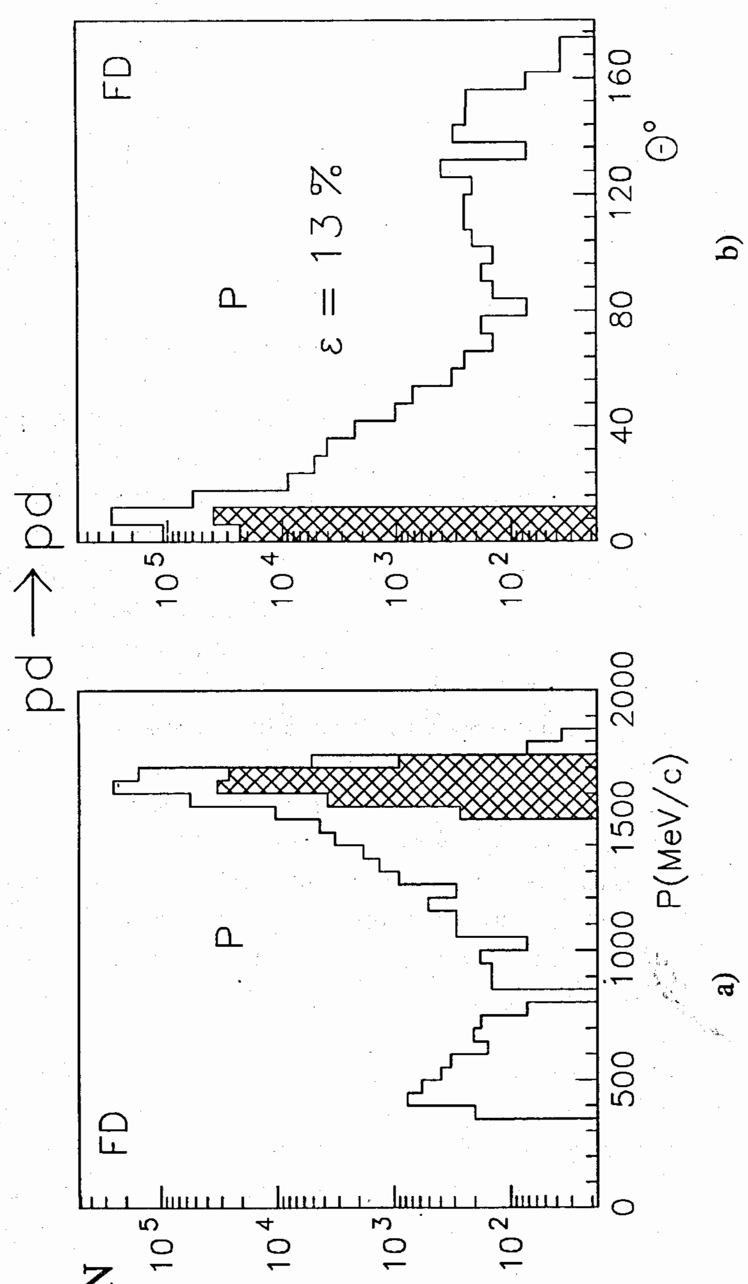

Fig.4. Momentum (a) and angular (b) distribution of protons from the elastic process $pd \rightarrow pd$. The shaded part of the histogram corresponds to the protons that hit the detector.

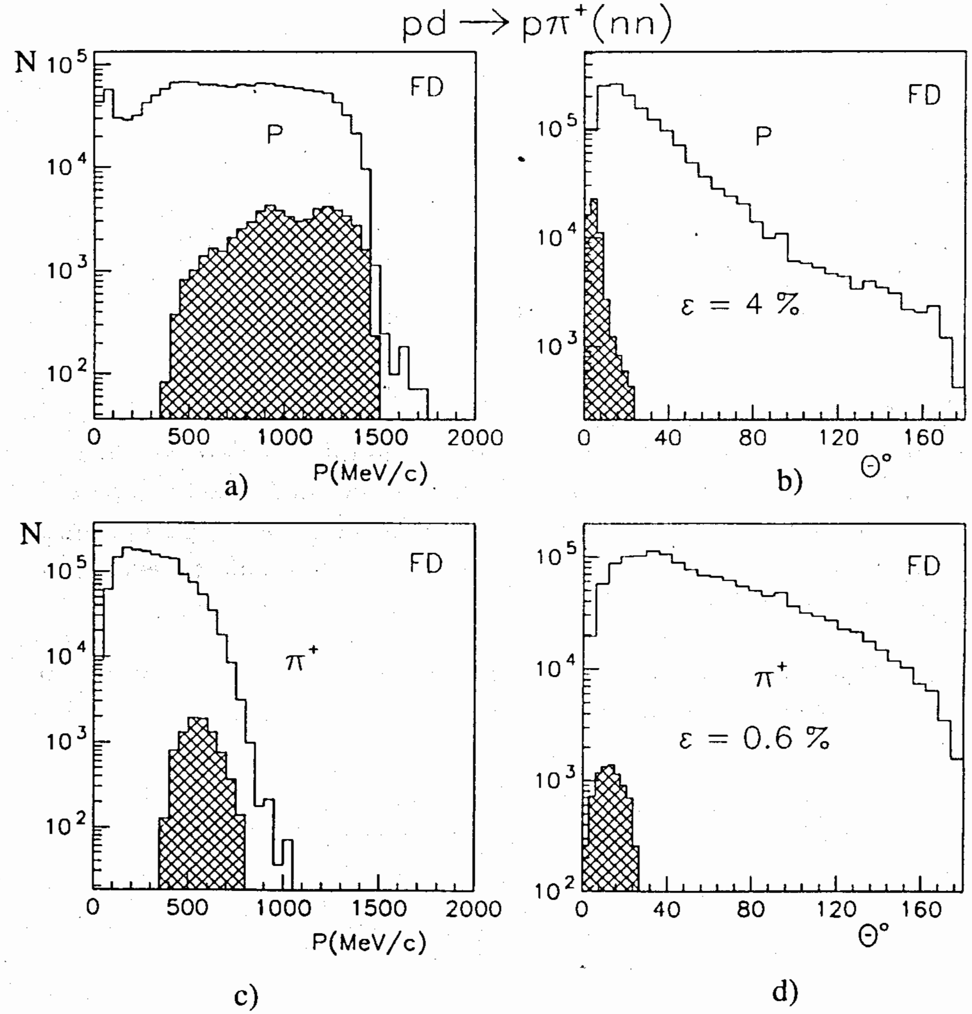

Fig.5. Momentum (a) and angular (b) distribution of protons and momentum (c) and angular (d) distribution of π^+-mesons from the reaction $pd \rightarrow p\pi^+(2n)$. The shaded part of the histogram corresponds to the detected particles.

figures the spectra of particles which traversed the experimental setup and reached the last scintillation hodoscope in FD are shown by shading. A share of protons that hit the detector amounted to 4%, a share of pions to 0.6%.

(3) The next background channel is the reaction $pd \to pp(n\pi^\circ)$. The momentum and angular spectra of protons from this reaction along with the spectra of protons detected in the FD arm are shown in Figs. 6.a,b. One can see that a wide area of momentum is detected in comparison with the spectrum of protons from the deuteron break-up. Share of protons that hit the detector is equal to 6%.

Spectra of Secondaries . In order to estimate the ratio of useful and background events we calculated the number of detected events in BD and FD detectors as well as the simultaneously detected particles for all reactions considered. The ratio of the background events from reactions (1,2,3) to the deuteron break-up events is presented in Table 2 for BD, FD and BD&FD coincidence.

Table 2. The ratio of detected protons from useful events to (π, p, d) from background ones in BD, FD and $BD\&FD$ coincidence.

$N_p(ppn) : N(background)$	BD	FD	$BD\&FD$
$N_p : N_p$	8:1	1:3	25:1
$N_p : N_{\pi^+}$	2:1	10:1	3:1
$N_p : N_d$	—	500:1	—

The distribution of all detected particles along the hodoscope transverse axis is presented in Fig. 7.a,b for the BD and FD hodoscopes respectively. The shaded area corresponds to background events. It is seen that in the BD hodoscope the relative counting rate distribution for background pions and protons as well as for the pion background in the FD hodoscope is flat. As it was noted above, the counting rate for protons in the FD hodoscope is

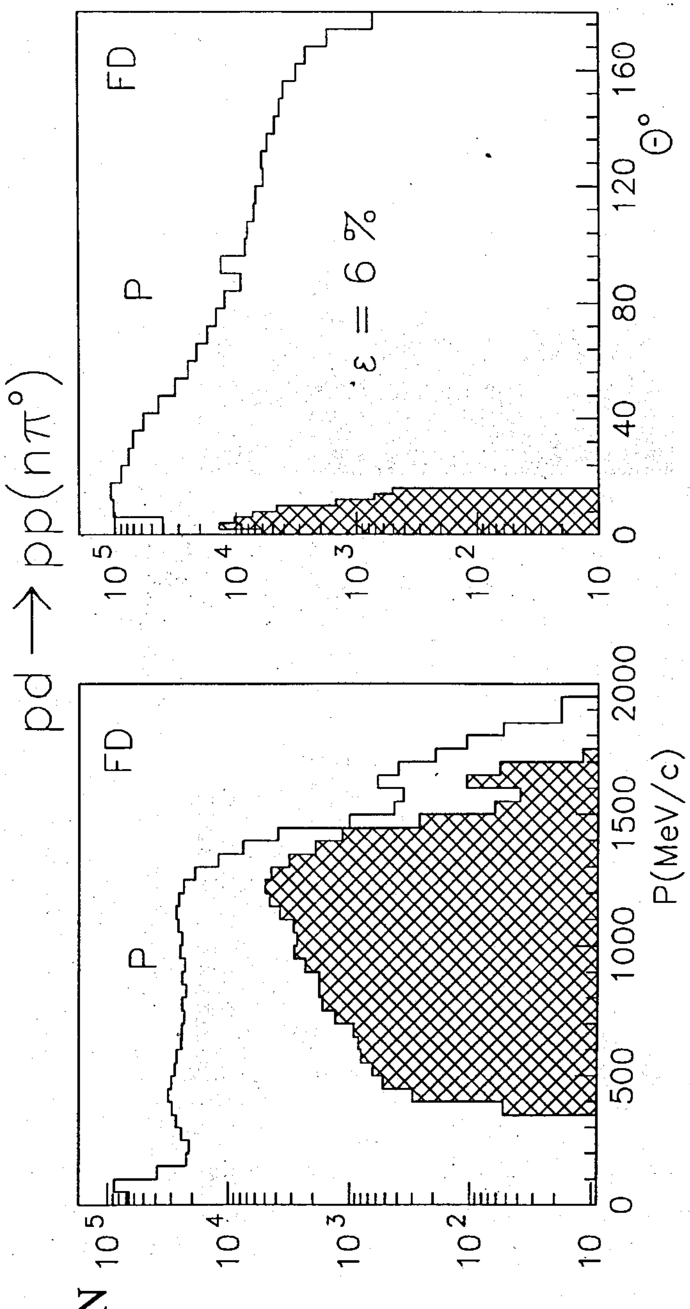

Fig.6. Momentum (a) and angular (b) distribution of protons from the reaction $pd \to pp(n\pi^\circ)$. The shaded area corresponds to the protons that hit the detector.

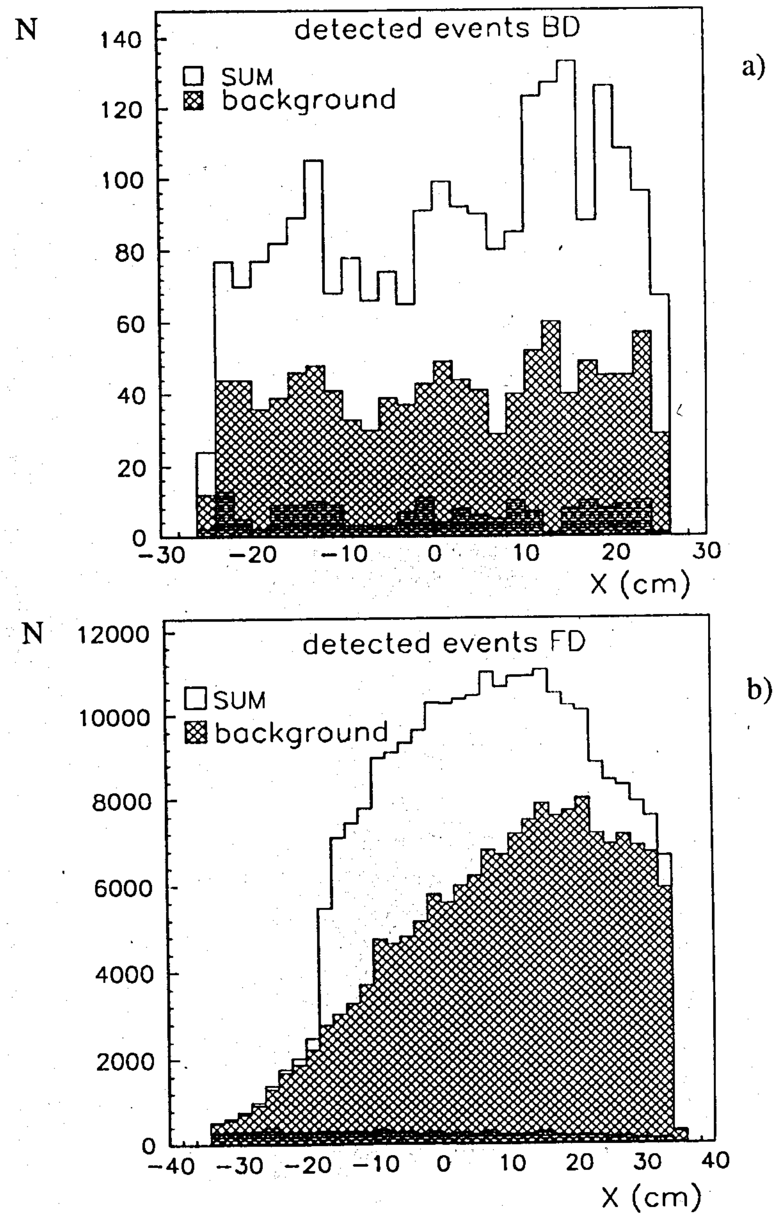

Fig.7. Distribution of all detected particles along the transverse axis of the BD(a) and FD(b) hodoscopes. The point $x = 0$ corresponds to the hodoscope center. The shaded area corresponds to the background events from reactions (1,2,3).

corrected near the beam pipe (small angles) by a factor of two.

The momentum distributions of the same events are shown in Fig. 8.a,b. From the spectrum shown in Fig. 8.b one can conclude that different kind of reactions are distinguished in this spectrum even without inclusion of information from BD. Here the spectrum of protons from the reaction $pd \rightarrow ppn$ that reached the detector (solid line) is given along with the spectra of protons from elastic scattering (shaded) (1) and inclusive protons from background processes (2) and (3) (shaded with wide gap). A spectrum of π mesons (black area) from reaction (2) is also shown. One can see that the overlap takes place mainly for spectra of protons from the mesonless deuteron break-up and elastic scattering. As is seen from the detected particle spectra in the BD system (see Fig. 8.a), there are two parts in the proton spectrum from the deuteron break-up events. The first (left one, soft) corresponds to the spectator mechanism [15] and the right one mainly belongs to the inelastic processes like Δ formation in the intermediate state [15].

From Table 2 and Fig. 8.a it is evident that the background events detected in the BD system will contain mainly π^+ mesons from reaction (2). In Fig.9 the momentum spectra of all particles detected in the BD system are shown for events in which the corresponding fast particle was detected in coincidence in the FD system. For these events protons from the deuteron break-up belonging to the 'spectator mechanism' are highly suppressed. This means that the experimental setup is adequately designed for the deuteron break-up investigation in the kinematic range far from quasi-free nucleon-nucleon scattering [2],[3]. It is obvious that in coincidence the ratio of useful events to background ones becomes better, especially for background protons.

Possibility of Background Suppression. As was mentioned above, the BD hodoscope consists of two parallel planes of scintillation counters. The counter thickness is equal to $5\,mm$ for the first and $20\,mm$ for the second one. In paper [16] the particle (π, K, p)

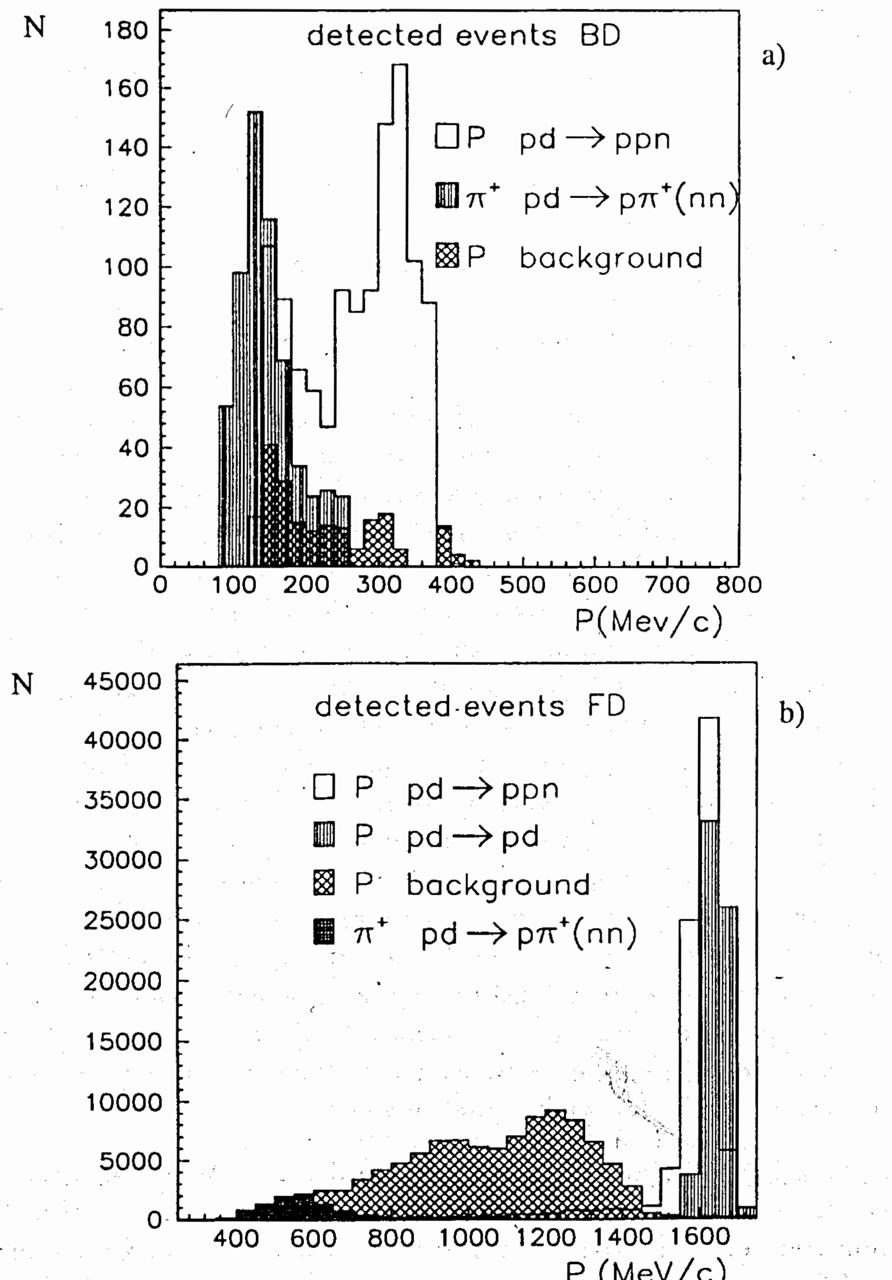

Fig.8. Momentum distribution of the particles that reached the BD(a) and FD(b) detectors from the reaction $pd \to ppn$ and background processes (1,2,3).

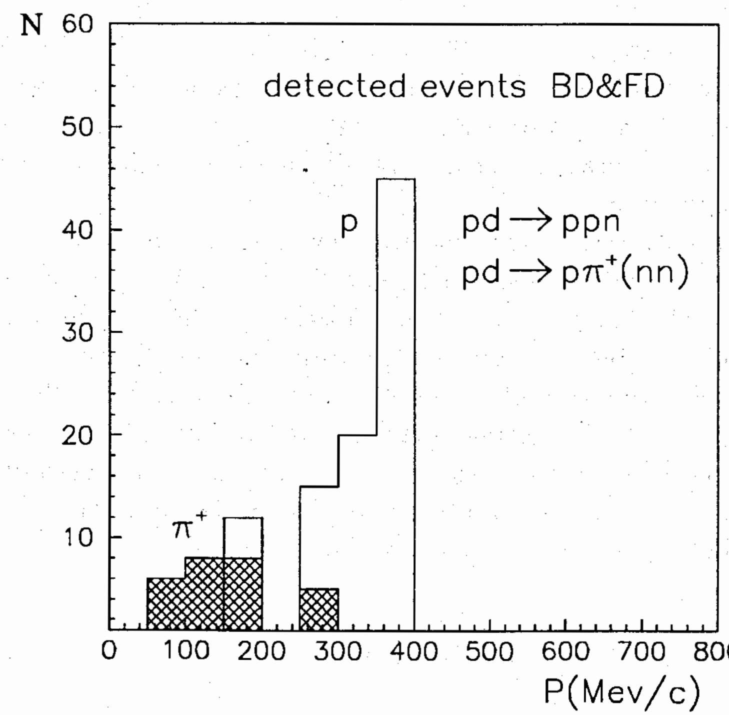

Fig.9. Momentum spectra of particles reaching the BD detector from events detected in BD and FD coincidence.

separation using these hodoscopes was considered. Energy losses in scintillation counters were investigated. The particle separation level was estimated with respect to deposited energy and the threshold level. The relative thresholds x for the counters with the same indices (n) were determined as follows $x = c_n^1 \overline{\Delta E_n^1}$ *and* $x = c_n^2 \overline{\Delta E_n^2}$, where $\overline{\Delta E_n^i}$ are the average energy losses in the n-th pair of elements of hodoscopes $i = 1, 2$, c_n^i is the calibration constants and will be determined individually for the n-th pair using the 2-dimensional plots of the deposited energy [16]. In Fig.10 the efficiencies of π, K, p detection are shown for all (8) counters as a function of the parameter x, The intrinsic resolution of the scintillation counters was neglected. The averaged π/p separation factor is higher than one order of magnitude.

As was mentioned above, the time correlation of particles in the BD and FD systems is assumed. On the one hand, all particles in the FD system have β close to 1 and they cannot be separated. The time separation can only be performed in the BD hodoscope. In Fig.11 the time of flight spectra (from the vertex to the BD hodoscope) in the 4th element (typical) are presented for π mesons (clear hist) and for protons (shaded). The intrinsic time resolution of 200 ps for scintillation counters is assumed. Defining the 'figure of merit' showing the quality of π/p separation as:

$$f = \frac{t_p - t_\pi}{\sigma_p + \sigma_\pi} ,$$

we got $f = 7$ for randomly generated particles for the whole BD hodoscope.

For the break-up event detection at the 'off-line' data processing the missing mass spectra can be considered. It is evident, that in the case of proton misidentification, the main background reaction is $pd \to p\pi^+(2n)$ with two neutrons in the final state. So in this reaction the missing mass (two neutrons) is drastically different from the missing mass (one neutron) in the mesonless break-up process. Under conditions considered above, the deuteron break-up

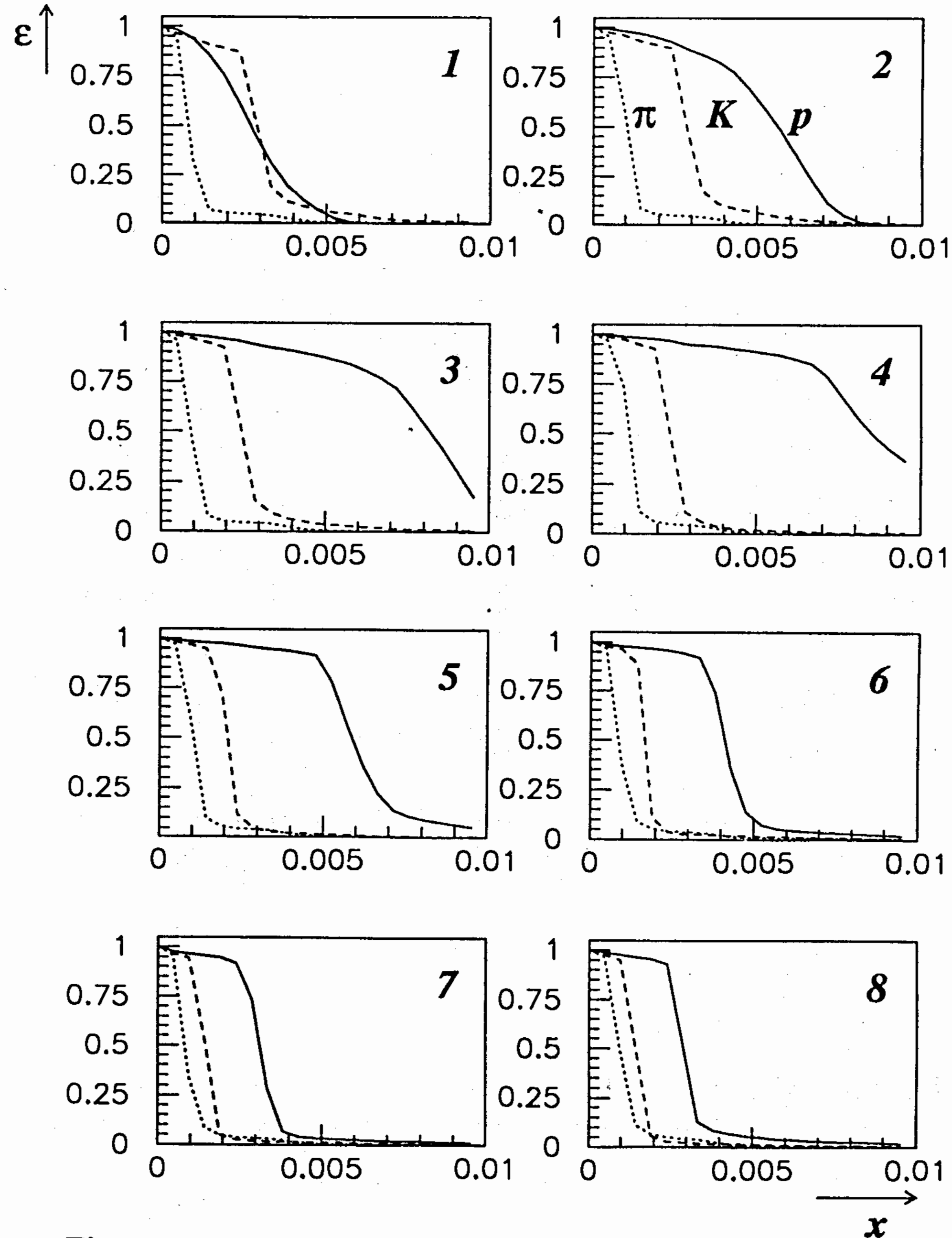

Fig.10. The π, K, p detection efficiencies in the BD hodoscope vs the x parameter defining the threshold.

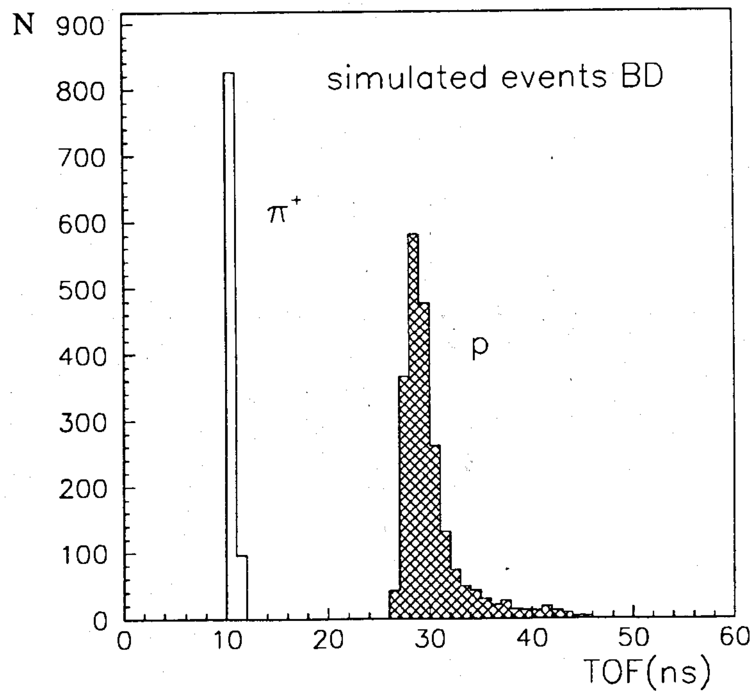

Fig.11. Delay time (TOF) spectra in the 4th element of the BD hodoscope for protons (shaded histogram) and π mesons.

events can be separated from background ones with high confidence level, even with a rather simple trigger device.

Expected Counting Rates. For estimation of counting rates of the BD and FD systems we used the luminosity value $L = 1.0 \cdot 10^{30}\, cm^{-2}\, s^{-1}$. After normalization to the number of interactions in the bubble chamber available experimental data have the following weight: one event corresponds to $0.46\,\mu b$ (with a precision better than 10%) irrespective of the reaction type.

The counting rate for the reaction i was estimated from the relation: $R_i = N_i\,\varepsilon_i\,0.46\,L \cdot 10^{-30}\,s^{-1}$, where ε_i are the BD and FD acceptances, N_i is number of events belonging to the reaction i. Estimation of the counting rates for the reactions with cross sections of the same order as the break-up cross section is presented in Table 3. As it is seen from Table 3, the expected ratio of useful events simultaneously detected in the BD and FD systems to the background is 3:1. The absolute counting rate for the useful break-up events is $\approx 1.2\, events \cdot s^{-1}$.

Table 3. The expected counting rate ($events \cdot s^{-1}$) at $1.7\,GeV/c$.

$pd \rightarrow \cdots$	BD	FD	$BD\&FD$
ppn(dir)	(p) 8	(p) $0.93 \cdot 10^3$	$(p\&p)$ 1.2
ppn(cex)	(p) 12	(p) –	$(p\&p)$ –
pd	(p) 0.4 (d) –	(p) $1.70 \cdot 10^3$ (d) 2	$(p\&d) \ll 1$ $(d\&p)$ –
$ppn\pi^\circ$	(p) 1.8	(p) $0.61 \cdot 10^3$	$(p\&p)$ 0.05
$pnn\pi^+$	(π^+) 10 (p) 0.3	(p) $0.66 \cdot 10^3$ (π^+) $0.10 \cdot 10^3$	$(\pi^+\&p)$ 0.4 $(p\&\pi^+) \ll 1$

Conclusion. Simulation of the setup performance has been carried out on the basis of the real experimental data obtained with the hydrogen bubble chamber at $3.3\,GeV/c$ deuteron momentum. The main background processes for the break-up reaction $pd \rightarrow ppn$

were considered and their kinematic characteristics were studied. The main conclusions are the following.

• Share of particles that hit the detector is estimated for different reactions. The ratio of particles from useful events to background, found for coincidence measurement, is rather high, even in absence of a particle type identification. The possibility of background suppression using the ΔE and TOF counters at the trigger level is estimated. The expected background suppression is high enough.

• The distribution of events over the areas of the BD and FD hodoscopes (relative counting rate) is obtained. Also, the expected counting rates for the BD and FD detectors is estimated. The absolute rate for the deuteron break-up events is $\approx 1.2\, events \cdot s^{-1}$ at the luminosity $L = 1.0 \cdot 10^{30}\, cm^{-2}\, s^{-1}$.

To summarize, one can conclude that the experimental setup allows the deuteron break-up investigation in the kinematic range far from the quasi-free nucleon-nucleon scattering, which is the main physical goal of experiment.

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