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THE REACTION CROSS SECTIONS OF n p INTERACTIONS AT $P_n = 1 \div 5$ GeV/c

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1. INTRODUCTION

To study np interactions in a momenta interval of 1÷5GeV/c, the 1m hydrogen bubble chamber of LHE, JINR has been irradiated with neutrons from the stripping of accelerated deuterons. The momenta and widths of the neutron spectra were: $P_n \pm \sigma P_n =$ $= (1.25 \pm 0.03)$, (1.73 ± 0.05), (2.23 ± 0.07), (3.83 ± 0.12), (4.35 ± 0.14) and (5.10 ± 0.17) GeV/c.

The irradiation conditions and the beam spectra of the incident neutrons are presented in paper [1]. Figure 1 shows, for example, the spectrum of the incident beam at $P_n = 3.83$ GeV/c.

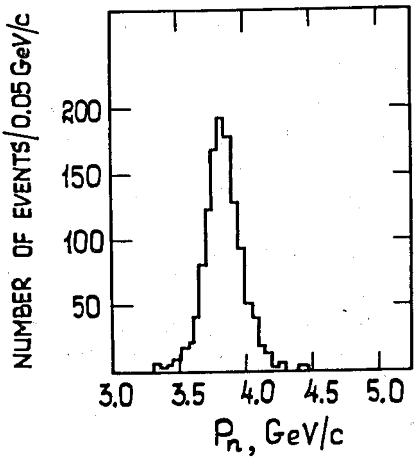


Fig.1. The momentum spectrum of incident neutrons at $P_n =$ $= 3.83$ GeV/c.

In this paper the results of the determination of the reaction cross sections are presented for 1-, 3- and 5-prong stars. The following reactions were studied:

5-prong stars $np \to pp\pi^+\pi^-\pi^-$, (1.1)

$\to pp\pi^+\pi^-\pi^-\pi^0$, (1.2)

$\to np\pi^+\pi^+\pi^-\pi^-$, (1.3)

$\to$ 5 charged + m neut. $(m \geq 2)$. (1.4)

3-prong stars $np \to pp\pi^-$, (2.1)

$\to pp\pi^-\pi^0$, (2.2)

$$np \to np\pi^+\pi^-, \quad (2.3)$$

$$\to d\pi^+\pi^-, \quad (2.4)$$

$$\to 3 \text{ charged } + m \text{ neut.} \quad (m \geq 2). \quad (2.5)$$

<u>1-prong stars</u>

$$np \to np, \quad (3.1)$$

$$\to pn \quad (\text{charge exchange}) \quad (3.1')$$

$$\to np + m\pi^0 \quad (m \geq 1) \quad (3.2)$$

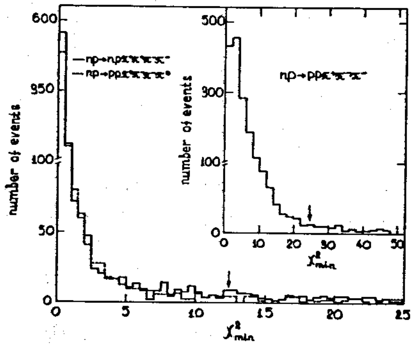
$$\to nn\pi^+ + m\pi^0 \; (m \geq 0). \quad (3.3)$$

Previously we have determined the topological cross sections for stars of these multiplicities [2] and studied the reaction $np \to d\pi^+\pi^-$ [3].

The presented results can be useful to study nucleon-nucleus and nucleus-nucleus interactions and to test various theoretical models of elementary particle interactions.

2. PROCESSING OF THE EXPERIMENTAL MATERIAL

The events chosen by the scanning with an efficiency of more than 90% have been measured with HPD and semi-automats PUOS. The geometrical reconstruction of events and the identification of the reaction channels were carried out using the corresponding programs [4]. Badly measured events and events outside the effective volume of the chamber were excluded from consideration.



<u>Fig.2.</u> The χ^2-distributions for the reactions (1.1), (1.2) and (1.3) at $P_n = 5.10$ GeV/c.

The further identification of the reaction channels was based on the analysis of the value of χ^2 for each event. Typical χ^2 distributions for 4c- and 1c-fit reactions are presented in <u>fig.2.</u> $c_4 = 25$ and $c_1 = 12.5$ were assumed to be confidence limits for 4c-fit and 1c-fit, respectively. If the values of χ^2 for two or more hypotheses of reaction channel were within the confidence interval for a given event, a visual estimation of the ionization was additionally used in order to identify the tracks of positive particles. This procedure was used for $P_{p,\pi^+} < 1100$ MeV/c on condition that the track of the particle has a dip angle of $|\alpha| < 45°$.

3. DETERMINATION OF THE REACTION CROSS SECTIONS FOR 5- AND 3-PRONG STARS

One of the difficulties to separate the reaction channels is the fact that a considerable number of events can simultaneously satisfy both hypotheses of 4c-fit (reaction (1.1) of 5-prong stars and (2.1) of 3-prong stars) and hypotheses of 1c-fit (reactions (1.2-1.3) and (2.2-2.3), respectively), i.e., it can happen for concrete 5- or 3-prong events that $\chi^2_{4c} < c_4$ and $\chi^2_{1c} < c_1$. The analysis of the missing mass MM^2 distributions shows that these events with $\chi^2_{4c} < c_4$, apart from the values of χ^2_{1c}, must be attributed to the 4c-fit reaction, i.e., to the reaction (1.1) of 5-prong stars or to the reaction (2.1) of 3-prong stars. This conclusion agrees with the calculations presented in paper [5] and shows that the hypotheses with a greater number of constraint equations should be preferred to separate the reaction channels characterized by different number of constraint equations. To support the foregoing, it should be additionally noted that there are no contradictions to the condition $\chi^2_{4c} < c_4$ at the identification of events using the ionization of positive tracks.

It is more complicated to separate the reaction channels for event with $\chi^2_{4c} > c_4$ if values for the two 1c-fit hypotheses are within the confidence limits, i.e., $\chi^2_{1.2} < c_1$ and $\chi^2_{1.3} < c_1$ for 5-prong stars or $\chi^2_{2.2} < c_1$ and $\chi^2_{2.3} < c_1$ for 3-prong stars. In this case the important criterion of correct separation of the "overlapping" hypotheses is the isotopic symmetry of the reactions (1.3) and (2.3). Due to this condition for the reactions (1.3) and (2.3), the momentum spectra of $\pi^-(\pi^+)$ mesons in the laboratory system must coincide with those of $\pi^-(\pi^+)$ mesons in the antilaboratory system, and the $\cos\theta^*$ distributions in the c.m.s. of π^+ and π^- mesons and of protons and neutrons must be mirror symmetrical relative to 0°.

The analysis has shown that the greater part of these "overlapping" events should be attributed to the channel with π^0 meson in the final state for the best agreement with the criterion of isotopic symmetry. The validity of this separation is confirmed by the results of simulating the reactions (2.2) and (2.3) [6]. In particular, approximately 77% of the "overlapping" events must be attributed to the reaction (2.2) at the momentum of incident neutrons $P_n = 5.10$ GeV/c.

Moreover, taking into account the criterion of isotopic symmetry allowed the corrections for the losses of low energy π-mesons to be determined.

Another difficulty in the determination of the reaction cross sections for 5- and 3-prong stars is the necessity of taking into account the contribution of background events to them. The events of the following two types are attributed to background ones:

a) events with more than one neutral particle in the final state produced by incident neutrons and imitating 1c-fit reactions;

b) events caused by the interaction of secondary neutrons, i.e., neutrons produced by the interaction of incident beam neutrons with a steel window of the chamber and an invisible volume of H_2.

Relative fraction of background events of the type b) were estimated in paper /2/ for the stars of various multiplicities.

It is rather easy to take into account the background for 5-prong stars.

However, the contribution of these background events to the 1c-fit reactions can be considerable for 3-prong stars that leads to a visible distortion on the shape of the MM^2 distributions, in particular to the appearance of "tails" in the right part of the distribution. Therefore a special procedure was used to take into account the contribution of background events to the reactions (2.2) and (2.3). The analysis has shown that on condition $\chi^2_{1c}<1$ the contribution of background to the events identified as reactions (2.2) or (2.3) gets essentially smaller. Based on the events selected using this condition, the following simulation of the MM^2 distributions was performed: the parameters of the tracks of registered particles were generated for each such an event using the rule

$$P_i^{mod} = P_i^{mes} + \Delta P_i \cdot \eta_j , \qquad (4)$$

where P_i^{mod} and P_i^{mes} are the new and measured values of an i-th parameter, respectively; ΔP_i its measuring error, and η_j a normal distributed random number. Then the value of MM^2 was calculated for the simulated event using the new values of parameters. A comparison between the simulated and experimental MM^2 distributions allowed one to obtain the weights of events to correct the experimental distributions. Figure 3 shows the MM^2 distribution for the reaction (2.3) at $P_n = 3.83$ GeV/c before and after the correction. This procedure is described in more detail in papers /6,7/. Figure 4 shows the $\cos\theta^*$ distributions in the c.m.s. of nucleons and π-mesons for the reaction (2.3) at $P_n = 5.10$ GeV/c. The symmetrical shape of these distributions around 0° testifying the isotopic invariance of the reaction (2.3) illustrates a sufficient reliability of the suggested procedure.

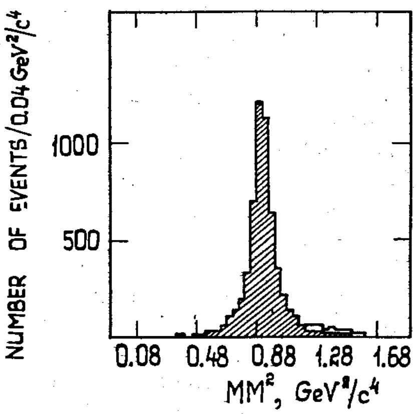
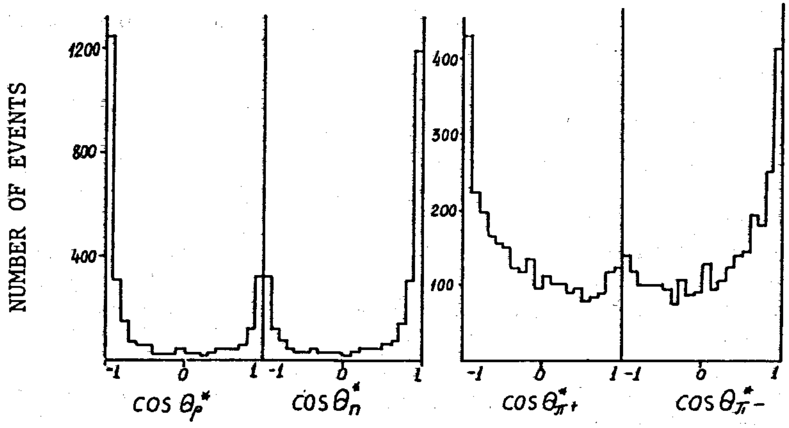


Fig.3. The MM^2 distribution for the reaction (2.3) at P_n = = 3.83 GeV/c. The blackened part corresponds to the data after correction.

Fig.4. The $\cos\theta^*$ distribution for nucleons and π-mesons from the reaction (2.3) at $P_n = 5.10$ GeV/c.



Another way to determine the contribution of background events to the reactions (2.2) and (2.3) for 3-prong stars is based on the use of real events of the experiment for this purpose. Such a method of simulation allows one to avoid difficulties in the choice of a definite matrix element of interactions and, moreover, to use the verified system of experimental data processing.

To simulate the n-p interactions due to secondary neutrons, use was made of 3-prong stars at the momenta of incident neutrons smaller than the nominal one, i.e., the data at $P_n = 3.83$ and 2.23 GeV/c were used for background simulation at P_n = = 5.10 GeV/c.

To simulate the reaction (2.5), i.e., 3-prong events with 5 or 6 particles in the final state, 5-prong stars were used at the same momenta of incident neutrons. The simulation of 3-prong stars was provided by excluding two charged tracks of 5-prong star using the definite rules.

The use of some estimative analogue of χ^2 for the background events simulated in this manner and the ionization identification of positive tracks of the events attributed to reaction (2.5) allowed one to determine the contribution of background events to reaction (2.5) and also to reactions (2.2) and (2.3). This method of computation of the background contribution is described in more detail in paper /6/.

It should be noted that use of both the method based on the simulation of the MM^2 distributions and the independent method of simulation using real 5- and 3-prong events has led to the coincident results in the determination of the cross sections of reactions (2.2) and (2.3).

To calculate the values of the cross sections, the formula was used:

$$\sigma_i = \frac{N_i}{N_{tot}} \sigma_{top} , \qquad (5)$$

where N_i is the number of events (weighted and corrected) identified as the process (i); N_{tot} is the total number of 5- or 3-prong events (without immeasurable events) registered in the working volume of the chamber; σ_{top} is the topological cross sections of 5- or 3-prong stars, respectively. The errors in the cross sections were calculated taking into account the errors of all terms in formula (5).

The obtained data of the reaction cross sections for 5- and 3-prong stars of n-p interactions are shown in Tables 2 and 3 and in figure 7a,b.

4. DETERMINATION OF THE REACTION CROSS SECTIONS FOR 1-PRONG STARS

To determine the reaction cross sections for 1-prong stars, the method was applied which is different from that used for 5- and 3-prong stars. The value of missing mass MM^2 and not the χ^2 value of individual hypotheses was taken as the main criterion in the separation of the channels of 1-prong stars. Figure 5 shows, for example, the MM^2 distribution at P_n = = 3.83 GeV/c. It should be noted that to calculate the values of MM^2 all positive particles (except simply identified π^+ mesons) were taken as protons.

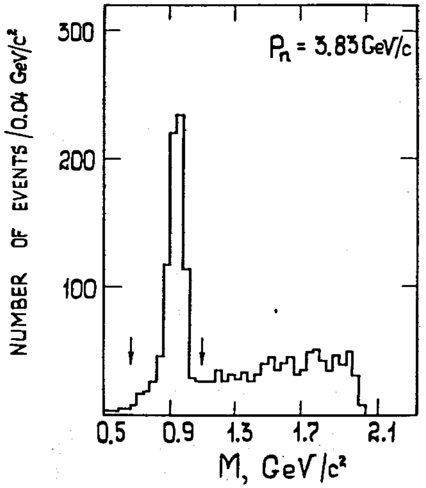


Fig.5. The MM^2 distribution for 1-prong stars at P_n =3.83 GeV/c; the limits of MM^2 for elastic channel are marked by arrows.

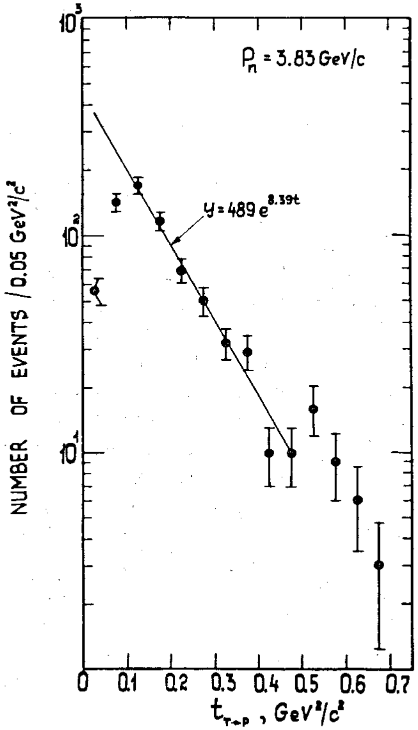


Fig.6. The $t_{T\to p}$ distribution for the reaction (3.1) at P_n = = 3.83 GeV/c. The solid curve is the result of the approximation of the data by the type A exp(bt) function in a |t| interval of 0.1 ÷ 0.5 GeV²/c².

The analysis of the MM^2 distributions allowed one to choose the limits of the MM^2 value corresponding to the events of the elastic channel, i.e., to the reactions (3.1) and (3.1 ex). These limits were equal to: (0.74÷1.06) GeV²/c⁴ for P_n = 1.25, 1,73 and 2.23 GeV/c, (0.66÷1.10) GeV²/c⁴ for P_n = 3.83 GeV/c and (0.66÷1.14) GeV²/c⁴ for P =5.10 GeV/c.

The probable contribution of the events of reaction (3.3) to the elastic channel was not greater than 1.2% for all P_n. This estimation was obtained on the basis of processing the events of the reaction $np \to pp\pi^-(m\pi^0, m \geq 0)$ that was isotopically conjugate with the reaction (3.3). To obtain the MM^2 distribution of the reaction (3.3), it was sufficient to use the events of the reaction $np \to pp\pi^-(m\pi^0)$ from 3-prong stars excluding two-proton tracks and attributing the proton mass to the remaining π-meson.

To estimate the contribution of the reaction (3.2) to the elastic channel, this reaction was simulated using the program FORS/8/ and taking into account the measuring errors of the proton track parameters. The analysis has shown that at $P_n = 5.10$ GeV/c only 2.5% of events of the reaction (3.2) can be erroneously attributed to the elastic channel, and this part decreases with decreasing P_n. Taking into account that the cross section of the reaction (3.2) is some times smaller than the elastic one at the considered momenta of incident neutrons, one can conclude that the contribution of events of the reaction (3.2) to the elastic channel is not greater than 1%.

Figure 6 shows the squared momentum transfer distribution from target to scattered protons $t_{T\to p}$ at $P_n = 3.83$ GeV/c. The deficiency of events with small $t_{T\to p}$ is clearly observed which is due to the difficulty of registration and measurement of the tracks of low energy protons with short ranges. To determine the corrections to the losses of such events, the $t_{T\to p}$ distribution was approximated by the type $A\exp(bt)$ function at an interval of $0.1\ GeV^2/c^2 \le |t| \le 0.5\ GeV^2/c^2$. The further extrapolation of the data to the value of $|t| = 0$ allowed one to calculate the coefficients of correction to the losses of slow protons a_p^{CORR}. Table 1 presents the approximation parameters b and the coefficients a_p^{CORR} at various momenta of incident neutrons.

Table 1

P_n (GeV/c)	1.25	1.73	2.23	3.83	5.10
b (GeV^{-2}/c^2)	5.18±0.46	6.58±0.52	7.03±0.50	8.39±0.51	8.64±0.56
a_p^{CORR}(%)	17	27	27	30	37

The cross section of elastic scattering (including charge exchange) was calculated by the formula:

$$\sigma_{el} = \frac{N_{el}}{N_{1\,tot}} \cdot \sigma_{1\,tot}\ , \qquad (6)$$

where N_{el} is the number of elastic scattered events taking into account all corrections, $N_{1\,tot}$ the total number of 1-prong stars and $\sigma_{1\,top}$ the topological cross sections of 1-prong stars. The

Table 2

P_n (GeV/c)	3.83	4.35	5.10
$\sigma_{pp\pi^+\pi^-\pi^-}$ (mb)	0.37±0.04	0.48±0.03	0.64±0.04
$\sigma_{pp\pi^+\pi^-\pi^-\pi^0}$ (mb)	0.09±0.01	0.20±0.02	0.39±0.03
$\sigma_{np\pi^+\pi^+\pi^-\pi^-}$ (mb)	0.12±0.02	0.28±0.02	0.49±0.04
$\sigma_{5\text{-ch.}+m\ neut.}$ (mb)	0.03±0.01	0.06±0.01	0.19±0.01
$\sigma_{5\,top.}$ (mb)	0.61±0.04	1.02±0.06	1.70±0.08

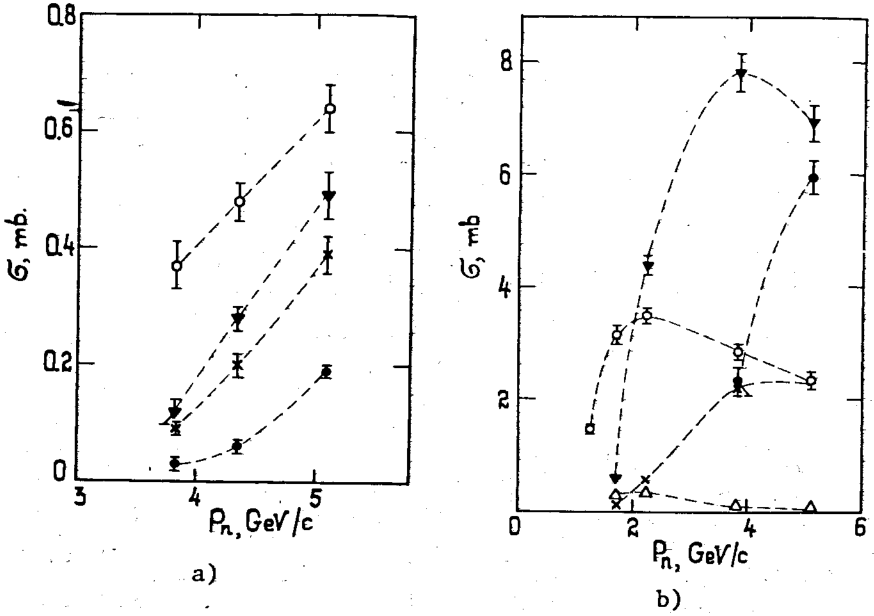
Table 3

P_n (GeV/c)	1.25	1.73	2.23	3.83	5.10
$\sigma_{pp\pi^-}$ (mb)	1.45±0.06	3.15±0.14	3.46±0.15	2.84±0.12	2.36±0.11
$\sigma_{pp\pi^-\pi^0}$ (mb)		0.10±0.01	0.56±0.05	2.21±0.13	2.27±0.12
$\sigma_{np\pi^+\pi^-}$ (mb)		0.58±0.04	4.35±0.18	7.80±0.32	6.89±0.28
$\sigma_{d\pi^+\pi^-}$ (mb)		0.27±0.02	0.33±0.02	0.05±0.02	0.03±0.02
$\sigma_{3\text{-ch.}+m\ neut.}$				2.31±0.24	5.95±0.30
$\sigma_{3\,top.}$ (mb)	1.45±0.06	4.10±0.15	8.7±0.3	15.2±0.5	17.5±0.5

Table 4

P_n (GeV/c)	1.25	1.73	2.23	3.83	5.10
σ_{el} (mb)	29.65±1.36	25.0±1.31	20.77±0.97	15.34±0.83	13.03±0.75
$\sigma_{ch.ex.}$ (mb)	9.62±0.47	5.00±0.33	2.67±0.22	0.89±0.20	0.46±0.08
$\sigma_{np+m\pi^0}$ (mb)	5.00±1.48	7.65±1.45	8.51±1.15	6.31±1.04	4.14±0.95
$\sigma_{nn\pi^++m\pi^0}$ (mb)	1.45±0.06	3.25±0.14	4.02±0.18	5.05±0.18	5.63±0.34
$\sigma_{1\,top.}$ (mb)	36.1±0.6	35.9±0.6	33.3±0.6	26.7±0.6	22.8±0.5

events of the elastic channel were attributed to the charge exchange elastic scattering if the scattered proton flew into forward hemisphere in the reaction c.m.s., i.e., $\sigma_{ex} = \sigma_{el}(\cos\theta_p^* > 0)$. The function of the type $\sigma_{ex} = AP_n^{-k}$ was used to approximate the dependence between σ_{ex} and the momentum of



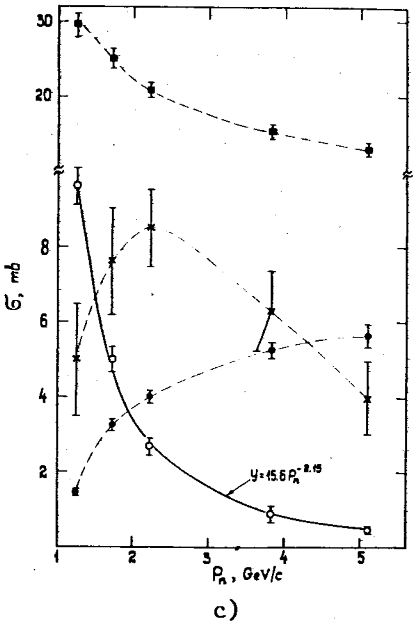


Fig.7. The reaction cross sections of n-p interactions;
a) 5-prong stars:
o – $np \to pp\pi^+\pi^-\pi^-$,
x – $np \to pp\pi^+\pi^-\pi^-\pi^o$,
▼ – $np \to np\pi^+\pi^+\pi^-\pi^-$,
● – np → 5 char. + m neut.
b) 3-prong stars:
o – $np \to pp\pi^-$,
x – $np \to pp\pi^-\pi^o$,
▼ – $np \to np\pi^+\pi^-$,
Δ – $np \to d\pi^+\pi^-$,
● – np → 3 char. + m neut.
c) 1-prong stars:
■ – np → np,
o – np → pn (charge exchange)
x – $np \to np + m\pi^o$
● – $np \to nn\pi + m\pi^o$.
The solid line for the reaction np → pn (charge exchange) is the results of the approximation by the function of the type AP_n^{-k} at A = 15.6 and k = 2.15. The dotted lines are drawn by hand.

incident neutrons, where P_n is the momentum of the neutron beam in GeV/c. The following values of the coefficients were obtained: A = (15.6±0.8) mb, k = (2.15±0.08) with the value of χ^2 divided by the number of degrees of freedom equal to 0.6.

Due to isotopic invariance, the cross section of the reaction (3.3) is equal to that of the reaction $np \to pp\pi^-(m\pi^o, m \geq 0)$, the value of which is known from the data of 3-prong stars considered above.

The cross section of the reaction (3.2) was calculated by the formula:

$$\sigma_{np(m\pi^o,\ m \geq 1)} = \sigma_{1\ top} - \sigma_{el} - \sigma_{nn\pi^+(m\pi^o,\ m \geq 0)} \quad (7)$$

The obtained data of the reaction cross sections for 1-prong stars of n-p interactions are shown in Table 4 and in fig.7c.

5. CONCLUSION

In conclusion it should be noted that the use of the monochromatic neutron beams combined with such a high-precision apparatus as the 1m hydrogen bubble chamber of LHE, JINR has proved to be extraordinary successful. In consequence, it was possible to determine the cross sections of the reactions of n-p interactions at the momenta of incident neutrons 1÷5 GeV/c to a considerably higher precision than in other experiments /9/.

The authors consider it their pleasant duty to express their gratitude to the laboratory assistants of the neutron group at LHE and to the specialists from the HPD and PUOS groups at LCTA for carrying out measurements and for their help in data processing.

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