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Study of the $\pi^- n \longrightarrow \pi^-\pi^- p$ reaction at 430 MeV energy

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Abstract. The total cross-section for the $\pi^- n \rightarrow \pi^-\pi^- p$ reaction has been measured at a pion kinetic energy of 430 MeV in a deuterium bubble chamber. The cross-section value was found to be 0.197±0.016 mb that is much smaller than the predictions of the chiral perturbation theory. The differential spectra are compared with calculations made in the framework of the model of Bolokhov *et al.*

PACS. 13.60.Le Meson production – 13.85.Lg Total cross-sections

1 Introduction

The recent few years have brought a number of measurements of the $\pi N \rightarrow \pi\pi N$ reaction at energies close to the threshold. One of the main goals of these investigations was the extraction of the S-wave, isospin-0,2 $\pi\pi$-scattering lengths. In addition, these production processes certainly are of interest due to their important role in the low-energy physics of elementary particles and nuclei. It was shown that the low-energy experimental data for $\pi N \rightarrow \pi\pi N$ are consistent with the assumption of isospin symmetry [1] as well as threshold predictions of chiral perturbation theory [2,3]. An important progress in the understanding of $\pi N \rightarrow \pi\pi N$ reactions was due to the paper of Olsson and Turner [4], who calculated the leading contributions near threshold using an almost model-independent Lagrangian. They showed, under rather general assumptions, that the nature of the chiral-symmetry breaking can be characterized by the single symmetry-breaking parameter ξ. The $\pi\pi$-scattering lengths are expressed in terms of this parameter too. The chiral perturbation theory (and its extensions) is applied strictly at the threshold of the single-pion production reactions, where as a rule the statistics is rather poor because of the smallness of the cross-sections. As a result the value obtained in different papers [1,5,6] disperses in a broad range, $-0.6 \leq \xi \leq -0.2$, with errors not less than 0.1. Experimentalists are forced to move to the above-threshold region of energies because the pion production cross-section grows faster than T^2, where T is the energy above threshold in the c.m.s. In this case an accurate extraction of scattering lengths at large extent depends on a correct understanding of the production mechanism in the above-threshold region, because here other diagrams together with pole and contact terms contribute to the reaction amplitude.

It is important here to know the role of contributions from tails of the $N^*(1440)$ and $\Delta(1232)$ baryon resonances, which determine almost wholly the mechanism of the process at higher energies. Hence in this region experimental data are needed too. Certain models [7,8] developed for the pion production above threshold pretend to describe the experimental data up to an incident pion kinetic energy of 400 MeV.

In the energy range 400–600 MeV, experimental data on the reaction $\pi^+ p \rightarrow \pi^+\pi^+ n$ are rather scarce and the statistics consists of tens of events. The poor statistical accuracy is due to experimental difficulties: apart from the smallness of the cross-section, the single-pion production reaction has the strong background of the elastic $\pi^+ p$-scattering which also has two positive charged particles in the final state.

For these reasons, we investigated the charge-conjugated reaction

$$\pi^- n \longrightarrow \pi^-\pi^- p\,, \tag{1}$$

using a bubble chamber filled with deuterium as a neutron target.

2 Measurements and experimental results

To determine the cross-section of the process $\pi^- n \rightarrow \pi^-\pi^- p$, we have selected the events for the reaction

$$\pi^- d \longrightarrow \pi^-\pi^- pp \tag{2}$$

in the deuterium bubble chamber. Experimentally the presence of more than two charged particles in the final state is an advantage in using this reaction for it enables us

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to separate it unambiguously from the background (elastic and quasi-elastic processes) at the first stage of the film processing.

The experiment was carried out on the pion channel of the Petersburg Nuclear Physics Institute synchrocyclotron. A 35 cm bubble chamber filled with deuterium was exposed to the π^--meson of beam at a momentum of 555 MeV/c with a spread of 25 MeV/c (FWHM). The muon and electron contamination was determined from the time-of-flight spectrum and found to be negligible. The average number of incident particles per picture was about 10. A total number of 225 000 pictures was taken.

Monte Carlo simulation of the reaction (1) with the use of the FOWL code for a generation of events according to the phase space as well as the GEANT21 for particle tracking through the chamber showed that among the events generated there was none with a length of any negative track of the unmeasured curvature. On the other hand, there were the events without one proton track that corresponded to the case when one of the protons (the proton-spectator for the pion production reaction off a neutron) with a momentum smaller than 80 MeV/c is not visible in the chamber. To select the necessary three- and four-prong events with two negative charged tracks in the final state all films were scanned twice. The efficiency of the double scanning was 99.5%.

The selected events could belong not only to the negative-pion production but also to processes with Dalitz pairs in the final state (*e.g.*, the neutral-pion production). The events found were measured on semi-automatic measuring devices (PUOS) and geometrically reconstructed. To select the events for the reaction (2) the χ^2 criterion was used with 1% confidence level. Dalitz pair events were rejected by kinematical and ionization criteria. A total number of 207 events of the type (2) was selected.

To obtain the absolute cross-section value the total length of the beam tracks in the fiducial volume of the chamber was determined. To this aim, the number of beam tracks was counted in ten pictures taken from every fifty ones all along the exposure and the mean length of beam tracks was measured. The deuterium density was taken to be 0.136 g/cm^3 with 4% accuracy. The error given below for the cross-section value consists of the statistical one as well as errors of the measurement of the average track length(1%), track density per picture(3%), total number of useful pictures(1%) and deuterium density. The cross-section value for the reaction (2) has been found to be

$$\sigma(\pi^- d \to \pi^-\pi^- pp) = 0.194 \pm 0.016\,\text{mb}. \tag{3}$$

The purpose of the present experiment is to determine the cross-section of the reaction (1). So it is necessary to discuss the influence of the Fermi motion of the neutron in the deuteron and the Pauli exclusion principle for identical protons in the reaction (2) as well as to take into account screening effects.

The Fermi motion of the neutron in the deuteron could change the mean value of the effective incident pion momentum for the reaction (1) as well as the momentum distribution form. Figure 1 shows the momentum distribution of the slowest proton in the final state of the reaction (2) together with the Hulthen deuteron wave function distribution. One can see that the impulse approximation is valid with an exception for the region of large momenta. The momentum distribution of effective incident pion from the reaction (1) calculated from the final state of (2) taking into account two pions and fast proton only has the same mean value as that of the pion beam. But the first distribution has Gaussian width three times larger. Since the cross-section of the reaction (1) grows linearly with energy, this increase of the width has nothing to do with the mean energy, for which we intend to give a value of the cross-section of the reaction (1).

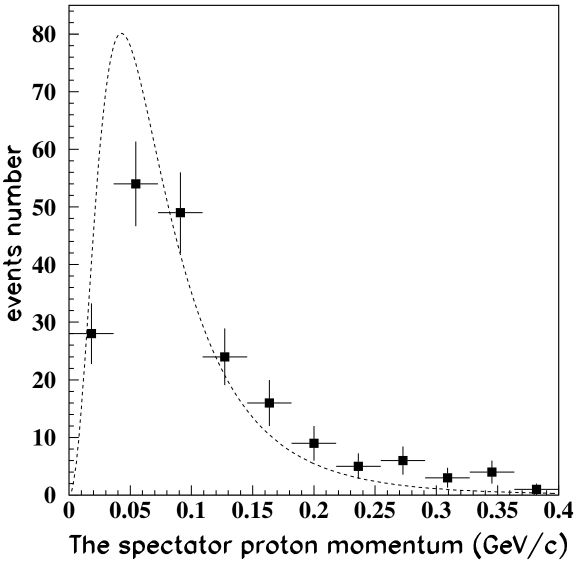

Fig. 1. Momentum distribution of the slow proton. The curve is the corresponding distribution for the Hulthen wave function.

The Pauli principle is important mainly at low energies when two low-energy protons have rather large probability to be in the same state. Simple estimates of the Pauli effect were made in the framework of the isobar model of the single-pion production. Such an estimate showed that Pauli principle could result in less than 2–4% decrease of the cross-section value. These estimates are model-dependent and, since the total error of the cross-section $\sigma(\pi^- d \to \pi^-\pi^- pp)$ measured in this experiment is above 8%, the last correction was not included in the magnitude of the cross-section off the free neutron.

The screening effect for the neutron in the deuteron was estimated in the framework of Glauber theory. It was assumed that screening corrections are identical for any channel of πN-collisions. Following the receipt given by Glauber theory [9], the negative-pion production cross-section on the deuteron is connected with that on the free neutron as follows:

$$\sigma_{\pi^- d} = \sigma_{\pi^- n} - \frac{1}{4\pi}\sigma_{\pi^- n}\sigma^{\text{tot}}_{\pi^- p}\left\langle\frac{1}{r^2}\right\rangle, \tag{4}$$

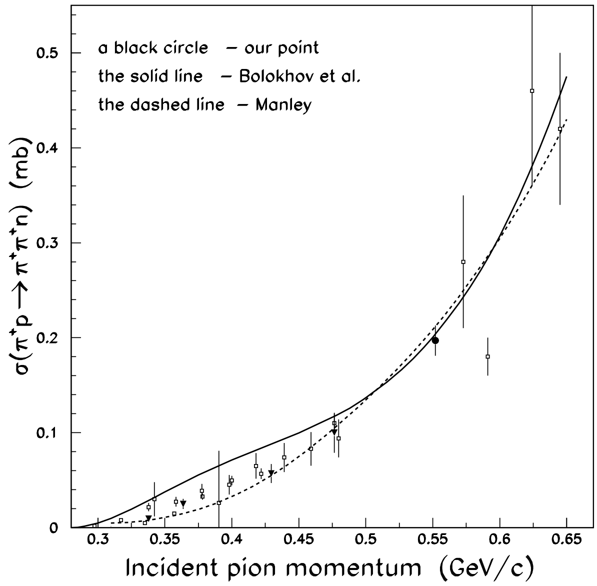

Fig. 2. Total cross-section for the $\pi^+ p \to \pi^+ \pi^+ n$ ($\pi^- n \to \pi^- \pi^- p$) reaction as a function of incident pion momentum. The dashed curve is the isospin analysis of ref. [1] and solid one is calculated in the framework of the model of Bolokhov *et al.* [8].

where the second term is the screening correction, $\sigma_{\pi^- n}$ and $\sigma^{\text{tot}}_{\pi^- p}$ are the cross-section sought on the free neutron and the total cross-section on the proton, respectively, and $\langle r^2 \rangle$ is the mean distance squared between the proton and neutron in the deuteron.

The distance between the proton and neutron in the deuteron is the double deuteron matter radius. The mean square matter radius (r.m.s.) equal to 1.967 fm was taken from the paper of Friar *et al.* [10], where this value was obtained from isotope-shift measurements. The total cross-section of the $\pi^- p$-scattering was taken to be 27.8 mb. Substituting these values and $\sigma(\pi^- d \to \pi^- \pi^- pp)$ into (3), one obtains that the screening correction to the deuteron cross-section amounts to 1.5% and is equal to 0.003 mb. Then the cross-section of the single-pion production off the free neutron is

$$\sigma(\pi^- n \to \pi^- \pi^- p) = 0.197 \pm 0.016\,\text{mb}. \tag{5}$$

In fig. 2, this value (black circle) is shown together with the data of others experiments [6,11–13] for $\pi^+ p \to \pi^+ \pi^+ n$ as well as the data for the reaction (1) obtained by us earlier [14] for four lower energies (black triangles). Curves in fig. 2 correspond to the isospin analysis by Manley [1] and to calculations carried out in the framework of the model by Bolokhov *et al.* [8]. Among all diagrams considered in [8], only those shown in fig. 3 are needed for a satisfactory description of the experimental data. They include one-pion exchange diagram and those at the tree level with the nucleon, the $\Delta(1232)$ and the $N^*(1400)$ baryons in the intermediate states. The parameters of the model were obtained by fitting to five total cross-section for five pion production reactions in the energy points near 430 MeV as well as to the differential distributions obtained by Kirz *et al.* at 357 MeV [11] and those of this experiment, which are presented below.

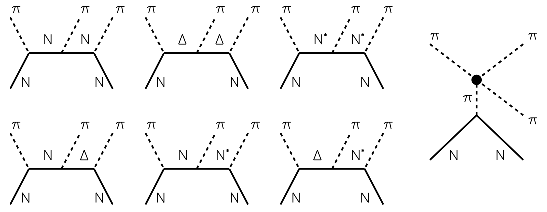

Fig. 3. Feynman diagrams taken into account in the framework of the model [8].

In the papers by Bernard *et al.* [2] and Jensen *et al.* [3], the single-pion production was studied in the frame of the relativistic baryon chiral perturbation theory at the tree level, with the $\Delta(1232)$ and $N^*(1440)$ baryon resonances. In [2] the exchanges by heavy mesons (σ, ρ) were also taken into account. In both papers, it was declared that they can describe satisfactorily the majority of existing data for total and differential cross-sections for incident pion energies up to 400 MeV. Since in refs. [2,3] the cross-sections were calculated only for the region below 400 MeV, we may compare our experimental value with those given by [2, 3] on the edge of this energy range. In both papers, a slow growth was predicted for the $\pi^+ p \to \pi^+ \pi^+ n$ reaction cross-section, and the values given for 400 MeV are about 0.4 mb and 0.35 mb, respectively, that is much larger than the value measured by us for 430 MeV. So the predictions of the chiral perturbation theory for the cross-section of this reaction are obviously overestimating. Of course, it is possible that the energy above 400 MeV is too high, and these approaches are not applicable here. An analysis of pion production through the baryon resonance formation in the intermediate states is more appropriate here. Such is the model of Bolokhov *et al.* [8].

As was mentioned above, the statistics for the reaction $\pi^+ p \to \pi^+ \pi^+ n (\pi^- n \to \pi^- \pi^- p)$ in the energy range 400–600 MeV amounted to tens of events only. Therefore so far it has been impossible to investigate the differential spectra and compare them to the theoretical calculations. Although the statistics for the present experiment is not large too, still it allowed us to carry out the analysis of one-dimensional spectra.

Figures 4a, b show the distributions of the events as a function of the pion and proton momentum in the c.m.s. of the $\pi^- n \to \pi^- \pi^- p$ reaction at 430 MeV. The curves normalized to the total number of events represent the phase space (dashed curve) and the results of the fit (solid one) carried out in the framework of the model [8] with the use of the diagrams of fig. 3. Although the curves differ a little from each other, the calculations within the model [8] reproduce the behavior of the experimental spectra more correctly. The situation with $M_{\pi^- \pi^-}$ and $M_{\pi^- p}$ invariant masses spectra is fairly similar (see figs. 5a and b). This is not a surprise, for the squares of invariant masses connect one to one with the c.m.s. energy of the third particle.

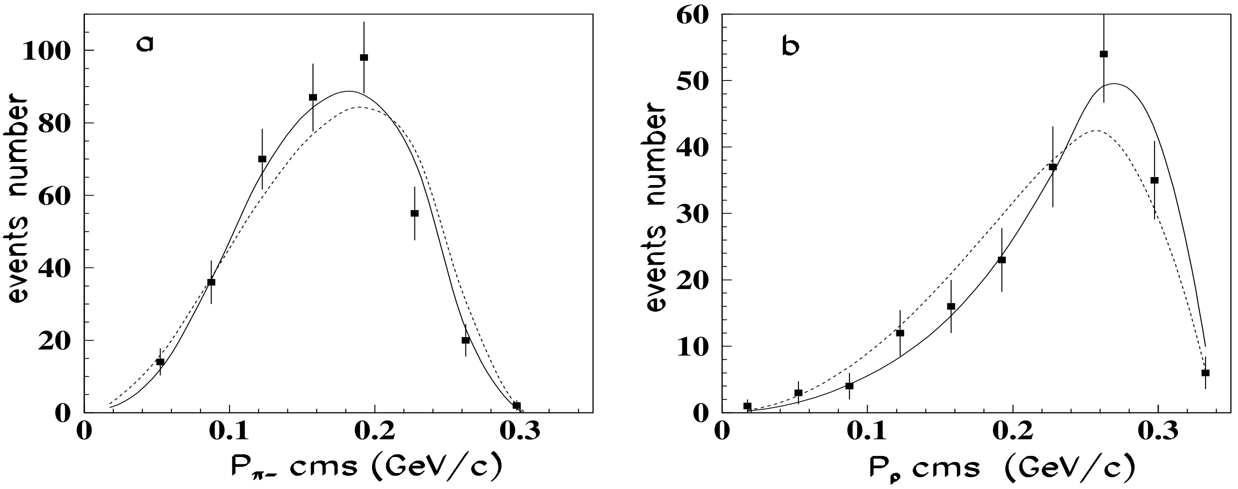

Fig. 4. The center-of-mass momentum spectra of pions and proton of the $\pi^- n \to \pi^- \pi^- p$ reaction. The dashed curve is the phase space distribution and the solid one is calculated in the framework of ref. [8].

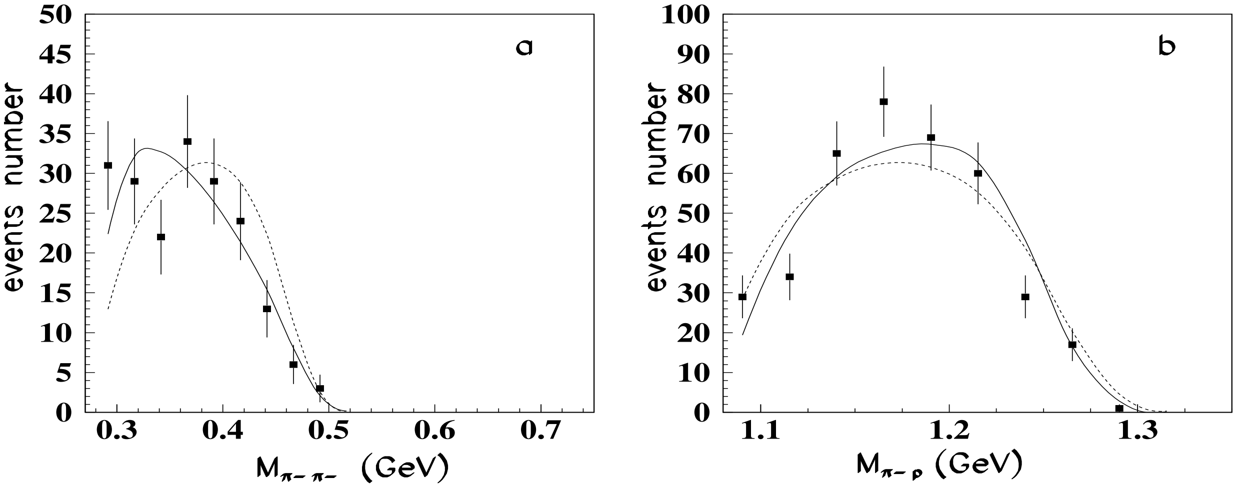

Fig. 5. Distributions of events as functions of the $M_{\pi^-\pi^-}$ and $M_{\pi^- p}$ invariant masses. The curves are the same as in fig. 4.

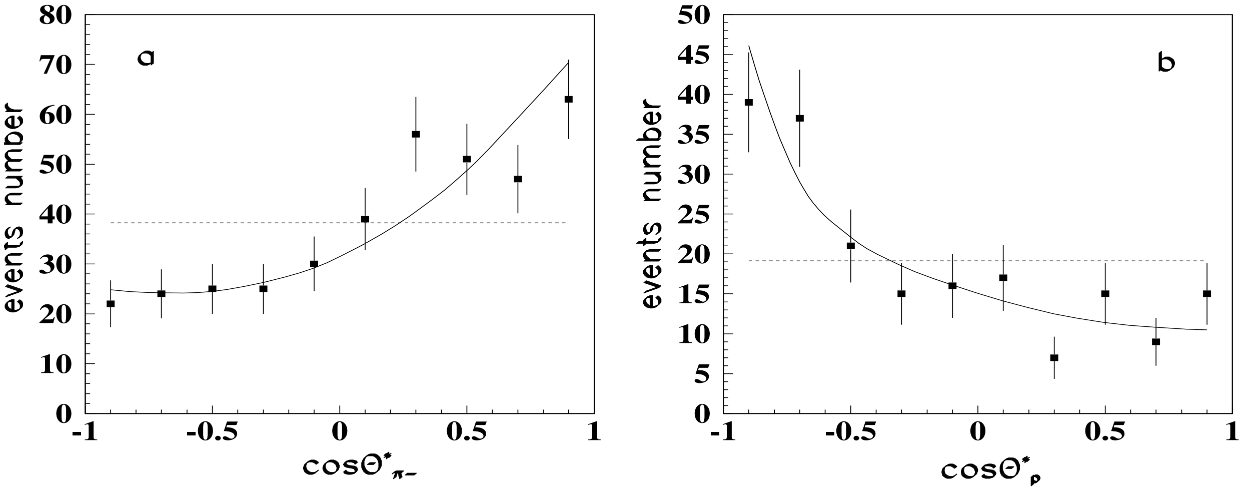

Fig. 6. Distributions of events as functions of the π^--meson and proton angles in the c.m.s. The curves are the same as in fig. 4.

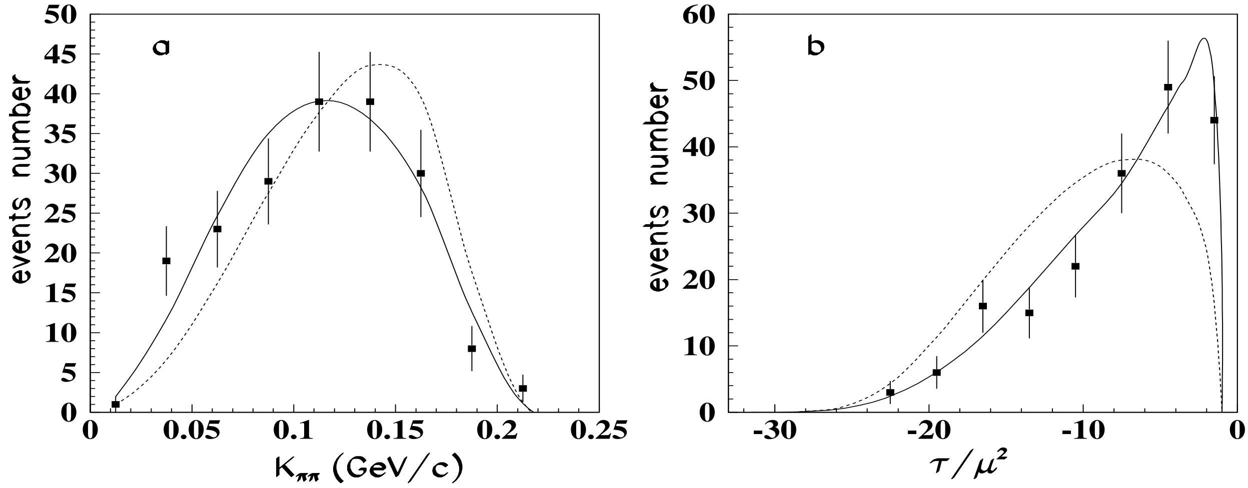

Fig. 7. a) Distribution of events as a function of the relative pion momentum in the dipion c.m.s. b) Distribution of events as a function of the square of momentum transfer. The curves are the same as in fig. 4.

The c.m.s. angular distributions of pions and the proton are shown in figs. 6a and b together with curves presenting the results of the above-mentioned fit. It is worth noting that the observed behaviour of the differential cross-section of this experiment is similar to that observed by Kirz *et al.* [11] at 357 MeV. The calculations of the Bolokhov *et al.* model for angular distributions agree excellently with both sets of data of these experiments.

Figure 7a shows the distribution of events as a function of the relative pion momentum $K_{\pi\pi}$ in the dipion c.m.s. The phase space distribution and the calculation within Bolokhov *et al.* model are similar here, though the latter is closer to the experimental distribution. In fig. 7b, one can see the distribution of the events as a function of the momentum square τ transferred to the proton, in m_π^2 units. Again, the dashed line represents the phase space, whereas the solid line shows the calculation within Bolokhov *et al.* model.

So the comparison of the various differential spectra with calculations in the frame of the model by Bolokhov *et al.* shows that to reach the agreement of the theory with experimental data in the energy range 450–550 MeV/c, one needs to include into theory not only one-pion exchange but also diagrams with the nucleon, the $\Delta_{33}(1232)$ and the $N^*(1400)$ in the intermediate states. The exclusion from the fit of any of the baryon resonances shown in fig. 3 results in a considerable disagreement between experimental data and the theory.

3 Conclusion

We have studied the single-pion production $\pi^- n \to \pi^- \pi^- p$ reaction, using as a neutron target a bubble chamber filled with deuterium. The obtained cross-section value coincides fairly well with the prediction of the isospin analysis by Manley [1] but disagrees with models developed for the description of the energy region of single-pion production a little bit above the threshold [2,3]. As a rule, the predicted values are much higher than the experimental magnitude. The fitting of various differential spectra obtained in [11] and in the present experiment allowed us to find parameters of the model [8] so that the theory describes quite well experimental data in the energy range 450–550 MeV/c.

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References

1. D.M. Manley, Phys. Rev. D **30**, 536 (1984).
2. V. Bernard, N. Kaiser, Ulf-G. Meissner, Preprint KFA-IKP(TH)-1997-05.
3. T.S. Jensen, F.F. Miranda, Phys. Rev. C **55**, 1039 (1997).
4. M.G. Olsson, L. Turner, Phys. Rev. Lett. **20**, 1127 (1968); Phys. Rev. **181**, 2141 (1969); Phys. Rev. D **6**, 3522 (1972).
5. H. Burkhard, J. Love, Phys. Rev. Lett. **67**, 2622 (1991).
6. M.E. Sevior *et al.*, Phys. Rev. D **48**, 3987 (1993).
7. E. Oset, M.J. Vicente-Vacas, Nucl. Phys. A **446**, 584 (1985).
8. A.A. Bolokhov *et al.*, Nucl. Phys. A **530**, 660 (1991); A.A. Bolokhov *et al.*, Preprint of PNPI 2197, Gatchina (1997).
9. V. Franco, R.J. Glauber, Phys. Rev. **142**, 1195 (1966).
10. J.L. Friar, J. Martorell, D.W. Sprung, Preprint LA-UR-97-2330 (1997).
11. J. Kirz, J. Schwartz, R.D. Tripp, Phys. Rev. **126**, 763 (1962).
12. C.P. Poirier *et al.*, Phys. Rev. **143**, 1092 (1966); G. Kernel *et al.*, Z. Phys. C **48**, 201 (1990); C.A. Buniatov *et al.*, Sov. Nucl. Phys. **21**, 308 (1975); M.G. Bowler *et al.*, Nucl. Phys. B **17**, 331 (1970); J. Debaisieux *et al.*, Nucl. Phys. **63**, 273 (1965).
13. M. Kermani *et al.*, Phys. Rev. C **58**, 3419 (1998).
14. A.V. Kravtsov *et al.*, Nucl. Phys. B **134**, 413 (1978).