Reaction of two pion production \( pd \to pd\pi\pi \) in the resonance region

Yuriy Uzikov\textsuperscript{1,2,3,*} and Nurbek Tursunbayev\textsuperscript{1,3,4,**}

\textsuperscript{1}Laboratory of Nuclear Problems, JINR, RU-141980 Dubna, Russia
\textsuperscript{2}Department of Physics, M.V. Lomonosov Moscow State University, RU 11991 Moscow, Russia
\textsuperscript{3}Dubna State University, RU-141980 Dubna, Russia
\textsuperscript{4}Institute of Nuclear Physics, Almaty, Kazakhstan

Abstract. The ANKE@COSY data on the reaction of two-pion production in the GeV region are analyzed within the theoretical model by Platonova and Kukulin. The model includes excitation of the dibaryon resonance \( D_{IJ} = D_{03}(2380) \) with the spin \( J = 3 \) and isospin \( I = 0 \) observed by the WASA@COSY in the reaction \( pn \to d\pi^0\pi^0 \), and its decay \( D_{03} \to D_{12} + \pi \to d + \pi + \pi \), where \( D_{12}(2150) \) is another dibaryon resonance. Distributions on the invariant masses of the final \( d\pi\pi \) and \( \pi\pi \) systems are calculated.

1 Introduction

Search for dibaryon resonances in two-nucleon systems has a long history (for review see [1]). At present one of the most realistic candidate to dibaryon is the resonance \( D_{IJ} = D_{03}(2380) \) observed by the WASA@COSY [2] in the total cross section of the reaction of two-pion production \( pn \to d\pi^0\pi^0 \), where \( I = 0 \) is the isospin and \( J = 3 \) is the total angular momentum of this resonance. The mass of the resonance 2.380 GeV is close to the \( \Delta\Delta \)-threshold, but its width \( \Gamma = 70 \) MeV is twice lower as compared to the width of the free \( \Delta \)-isobar. This narrow width is considered as the most serious indication to a non-hadronic, but most likely, quark content of the observed resonance state. Quark model calculations with presence of the hidden color allows one to explain the observed narrow width of this state [3]. On the other hand, in a pure hadronic picture with presence of the hidden color allows one to explain the observed narrow width of this state [3]. On the other hand, in a pure hadronic picture with presence of the hidden color allows one to explain the observed narrow width of this state [3]. On the other hand, in a pure hadronic picture with presence of the hidden color allows one to explain the observed narrow width of this state [3]. On the other hand, in a pure hadronic picture with presence of the hidden color allows one to explain the observed narrow width of this state [3]. On the other hand, in a pure hadronic picture with presence of the hidden color allows one to explain the observed narrow width of this state [3]. On the other hand, in a pure hadronic picture with presence of the hidden color allows one to explain the observed narrow width of this state [3]. On the other hand, in a pure hadronic picture with presence of the hidden color allows one to explain the observed narrow width of this state [3]. On the other hand, in a pure hadronic picture with presence of the hidden color allows one to explain the observed narrow width of this state [3].

As it was shown recently by Niskanen [7], the bound \( \Delta\Delta \)-system has the narrow width if one takes into account that a part of the energy of this system is assigned to internal motion of two \( \Delta \)'s and, therefore, cannot be used for decay of the \( \Delta \)-isobars.

Besides of the resonance behaviour of the total cross section of the reaction \( pn \to d\pi^0\pi^0 \) as a function of the total energy \( \sqrt{s} \), there is also resonance behavior of the differential cross section of this reaction as a function of the invariant mass of the final two-pion system \( M_{\pi\pi} \). This feature is known as the ABC effect first observed in the reaction \( pd \to ^3H\pi\pi \) in [8]. Now it is assumed that the ABC effect observed in \( pd \)- and \( dd \)- systems is caused just by excitation of the \( D_{03} \) resonance in the intermediate state [9]. Different mechanisms of the

*e-mail: uzikov@jinr.ru
**e-mail: tursunbayev.n@gmail.com
ABC effect in the reaction $pn \rightarrow d\pi^0\pi^0$ were discussed in [9]. One possible mechanism of the reaction $pn \rightarrow d\pi^0\pi^0$ suggested by Platonova and Kukulin in [10] involves sequential excitation and decay of two dibaryon resonances, $D_{03}(2380)$ and $D_{12}(2150)$.

The spin-parity of this resonance $J^P = 3^+$ was established by polarized measurements, however, information about its production (decay) channels is still non-complete. Recently a resonance structure was observed by the ANKE@COSY in the differential cross section of the two-pion production reaction $pd \rightarrow pd\pi\pi$ at beam energies 0.8-2.0 GeV with high transferred momentum to the deuteron at small scattering angles of the final proton and deuteron [11]. In the distribution over the invariant mass $M_{d\pi\pi}$ of the final $d\pi\pi$ system the resonance peak was observed at $M_{d\pi\pi} \approx 2.380$ GeV for beam energies 1.1 - 1.4 GeV [11] that is the mass of the isoscalar two-baryon resonance $D_{IJ} = D_{03}$, while the kinematic conditions differ considerably from that in [2]. Furthermore, the ABC-type effect was observed in [11] in the distribution of the invariant mass of two final pions $M_{\pi\pi}$.

Two mechanisms of this reaction involving excitation of the Roper resonance $N^*(1440)$ and two $\Delta$-isobars in one-loop diagrams depicted in Fig. 1 were studied in [12]. Both of these mechanisms predict too low cross section as compared to the data [11]. The reason is that these mechanisms contain the deuteron elastic form factor $S(Q)$ (clearly visible in the limit of the impulse approximation) that leads to low cross section at high transferred momentum $Q$ to the deuteron that is the case in the ANKE experiment [11]. The mechanism with the Roper resonance $N^*(1440)$ (Fig. 1, left) predicts proper position of the peak in the cross section of the reaction $pd \rightarrow pd\pi\pi$, while its width is twice large, but underestimates the cross section by two orders of magnitude. A similar result but with shifted peak was found for the $\Delta\Delta$-mechanism (Fig. 1, right). Another mechanism suggested in [10] for the reaction $pn \rightarrow d\pi^0\pi^0$ does not use the deuteron form factor but involves two dibaryon resonances, $D_{03}(2380)$ and $D_{12}(2150)$. We modify this model by inclusion of the $\sigma$-meson exchange between the proton and deuteron and apply it to the process $pd \rightarrow pd\pi\pi$ (Fig. 2). As it was found in [10], the ABC effect in the reaction $pn \rightarrow d\pi^0\pi^0$ can be explained if an additional decay mechanism is included, $D_{03} \rightarrow d\sigma \rightarrow d\pi^0\pi^0$, and partial restoration of the chiral symmetry in the $D_{03}$ dibaryon is assumed. Since this assumption is rather questionable and the contribution of this mechanism to the total cross section of the reaction $pn \rightarrow d\pi^0\pi^0$ is
rather small [10], we do not consider it here when analyzing the ANKE@COSY data [11]. Since not all required partial widths are known from the experiment [13] and theoretical analysis in hadronic picture [14] and quark model [3], we discuss mainly the shapes of the distributions over the invariant masses of the final $d\pi\pi$ and $\pi\pi$ systems.

2 The model

The transition amplitude for the mechanism depicted in Fig. 2 has the following form:

$$M_{\lambda_{d\pi}\lambda_{d}}^{Y}(pd \rightarrow pd\pi\pi) = M_{\lambda_{d}}^{Y}(p \rightarrow p'\sigma) \frac{1}{p_{\sigma}^{2} - m_{\sigma}^{2} + i m_{\sigma} \Gamma_{\sigma}} M_{\lambda_{d}}^{Y}(\sigma d \rightarrow d\pi\pi),$$

where $p_{\sigma}$, $m_{\sigma}$, $\Gamma_{\sigma}$ are the 4-momentum, mass, and the total width of the $\sigma$-meson, respectively; $\lambda_{i}$($\lambda'_{i}$) is the spin projection of the initial (final) particle $i$. The amplitude of the virtual process $p \rightarrow p\sigma$ is based on the phenomenological $\sigma NN$ interaction [15] and its spin-averaged form $|M_{\lambda_{d}}^{Y}(p \rightarrow p'\sigma)|^{2}$ is given in [12].

The amplitude of the subprocess $\sigma d \rightarrow d\pi\pi$ in Fig. 2 is

$$M_{\lambda_{d}}^{Y}(\sigma d \rightarrow d\pi\pi) = \sum_{\lambda_{2},\lambda_{3},\mu_{1},\mu_{2}} \frac{F_{D_{03} \rightarrow d\sigma} F_{D_{03} \rightarrow D_{12}\pi_{1}}}{p_{\lambda_{2}}^{2} - M_{D_{03}}^{2} + i M_{D_{03}} \Gamma_{D_{03}}} \frac{F_{D_{12} \rightarrow d\pi}}{p_{\lambda_{3}}^{2} - M_{D_{12}}^{2} + i M_{D_{12}} \Gamma_{D_{12}}} \times (1; \lambda_{2} \mu_{1} |3\lambda_{3}) Y_{2\mu}(\hat{q}) (2\lambda_{2} 1m_{1} |3\lambda_{3}) Y_{1m_{1}}(\hat{k}_{1}) (1; \lambda'_{3} 1m_{2} 2\lambda_{2}) Y_{1m_{2}}(\hat{k}_{2}) + (\pi_{1} \leftrightarrow \pi_{2}),$$

here the last term ($\pi_{1} \leftrightarrow \pi_{2}$) takes into account symmetrization over the final identical pions. $P_{D_{03}}$, $M_{D_{03}}$ and $\Gamma_{D_{03}}$ ($P_{D_{12}}, M_{D_{12}}$ and $\Gamma_{D_{12}}$) are the 4-momentum, the mass and the total width of the $D_{03}$ ($D_{12}$), respectively; $q$ is the 3-momentum of the initial deuteron in the c.m.s of the $D_{03}$, $k_{1}$ is the 3-momentum of the pion $\pi_{1}$ in the c.m.s of $D_{03}$, and $k_{2}$ is the 3-momentum of the pion $\pi_{2}$ in the c.m.s of the $D_{12}$. We use in Eq. (2) standard notations for the Clebsch-Gordan coefficients $(j_{1} m_{1} j_{2} m_{2} |JM)$ and spherical functions $Y_{lm}(\hat{k})$. The orbital momenta in the vertices $D_{03} \rightarrow \pi D_{12}$ and $D_{12} \rightarrow d\pi$ are $l_{1} = l_{2} = 1$ and in the vertex $d + \sigma \rightarrow D_{03}$ is $l = 2$. The vertex factors $F$ in Eq. (2) are defined as in [10]:

\begin{align*}
F_{D_{03} \rightarrow d\sigma}(q) &= \sqrt{\frac{8\pi \Gamma_{D_{03} \rightarrow d\sigma}(q)}{q^{5}}}, \\
F_{D_{03} \rightarrow D_{12}\pi_{1}}(k_{1}) &= \sqrt{\frac{8\pi \Gamma_{D_{03} \rightarrow D_{12}\pi}}{k_{1}^{3}}}, \\
F_{D_{12} \rightarrow d\pi}(k_{2}) &= \sqrt{\frac{8\pi \Gamma_{D_{12} \rightarrow d\pi}}{k_{2}^{3}}}.
\end{align*}

Here $M_{D_{03}}^{2} = P_{D_{03}}^{2}$, $M_{D_{12}}^{2} = P_{D_{12}}^{2}$, and $P_{D_{03}}$ ($P_{D_{12}}$) is the 4-momentum of the $D_{03}$ ($D_{12}$). The modules of 3-momenta $q$, $k_{1}$, $k_{2}$ are determined by the invariant masses of the particles in the vertices $\sigma dD_{03}$, $\pi D_{12} D_{03}$ and $\pi D_{12}$, respectively, via the triangle function $\lambda(m_{q}^{2}, m_{k_{1}}^{2}, m_{k_{2}}^{2})$:

$$q^{2} = \lambda(p_{\sigma}^{2}, m_{q}^{2}, P_{D_{03}}^{2})/(4P_{D_{03}}^{2}), \quad k_{1}^{2} = \lambda(m_{k_{1}}^{2}, P_{D_{12}}^{2}, P_{D_{03}}^{2})/(4P_{D_{03}}^{2}), \quad k_{2}^{2} = \lambda(m_{k_{2}}^{2}, m_{q}^{2}, P_{D_{12}}^{2})/(4P_{D_{12}}^{2}),$$

where $m_{q}$ and $m_{k_{i}}$ are the masses of the $\pi$-meson and deuteron, respectively; $k_{10}$ ($k_{20}$) is the value of the $k_{1}$ ($k_{2}$) at the resonance point $P_{D_{03}}^{2} = M_{D_{03}}^{2} = P_{D_{12}}^{2}$, $q_{0} = q(m_{q}^{2}, m_{k_{1}}^{2}, m_{k_{2}}^{2})$.

The invariant cross section can be written in the following form:

$$d\sigma = \frac{C_{T}}{(2\pi)^{6} 64 p_{f} s} \int \int |M_{\lambda_{d} \lambda_{d}}^{Y}(pd \rightarrow pd\pi\pi)|^{2} k' q' d\Omega_{k} d\Omega_{q} d\Omega_{p} dM_{\pi\pi} dM_{d\pi}. \quad (4)$$

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Here $s$ is the invariant mass of the initial $pd$ system, $p_i$ ($p_f$) is the 3-momentum of the initial (final) proton in the total c.m.s. of the reaction, $k$ is the pion momentum in the c.m.s. of the $\pi\pi$ system, and $q'$ is the momentum of the final deuteron in the c.m.s. of the final $d\pi\pi$ system. Eq. (4) determines distribution over the invariant mass $M_{\pi\pi}$ ($M_{\pi\pi}$) of the $d\pi\pi$ ($\pi\pi$) system. Integration intervals over variables $M_{\pi\pi}$, $\cos\theta_p$, and $\cos\theta_d$ are determined by experimental conditions [11] assuming azimuthal symmetry. In the experiment [11] the final pions $\pi\pi$ were not detected, therefore, both the $\pi^0\pi^0$ and $\pi^+\pi^-$ isoscalar pairs have to be taken into account in the present model. According to calculations [3], the ratio of the decay width $D_{03} \rightarrow d\pi^+\pi^-/D_{03} \rightarrow d\pi^0\pi^0$ is equal to 2 for unbroken isospin symmetry and 1.8 for the symmetry broken by the different masses of the $\pi^+$ and $\pi^0$ mesons. Therefore the isospin factor $C_T = 2.8$ is introduced in calculation of the $d\sigma$ in Eq. (4).

3 Numerical results and discussion

The following numbers were used in our calculations for the $D_{03}$ and $D_{12}$ resonances and the vertices parameters: $M_{D_{03}} = 2.380$ GeV, $\Gamma_{D_{03}} = 70$ MeV, $M_{D_{12}} = 2.15$ GeV, $\Gamma_{D_{12}} = 0.11$ GeV, $m_\sigma = 0.5$ GeV, $\Gamma_\sigma = 0.55$ GeV, $q_0 = 0.362$ GeV/c, $k_{10} = 0.177$ GeV/c, $k_{20} = 0.224$ GeV/c, $\lambda_{pD_{12}} = 0.12$ GeV. The values $\Gamma_{D_{12} \rightarrow d\pi^+} = 10$ MeV, $\lambda_{d\pi} = 0.18$ GeV and $\lambda_{d\pi} = 0.25$ GeV were obtained in [10]. The partial widths $\Gamma_{D_{03} \rightarrow d\sigma}$ and $\Gamma_{D_{12} \rightarrow d\pi^+}$ were not determined in [10] and are unknown at present. The results of our calculation based on Eq. (4) are shown in Figs. 3 and 4. One can see in Fig. 3 that maxima at low mass $M_{\pi\pi}$ observed in [11] are reproduced by the model (thick red lines in Fig. 3). This is caused by the behavior of spherical functions $Y_{lm}(\theta, \phi)$ in two vertices and the collinear kinematics in the ANKE experiment. If we go out of the collinear kinematics, when integrating over the full interval of the scattering angle $\theta_d$ of the final deuteron, this effect disappears (thin blue lines in Fig. 3).

The absolute value of the cross section of the reaction $pd \rightarrow pd\pi\pi$ is proportional to the product of the partial widths $D_{03} \rightarrow d\sigma$, $D_{03} \rightarrow D_{12}\pi$, $D_{12} \rightarrow d\pi$. The experimental data on some partial widths are given in [13]. The partial widths $\Gamma(D_{12} \rightarrow d\pi)$ and $\Gamma(D_{12} \rightarrow NN)$ were estimated in [16] from the analysis of the cross section of the reaction $pp \rightarrow d\pi^+$. The partial width $\Gamma(D_{03} \rightarrow d\pi^0\pi^0)$ is about 10 MeV [13]. If we assume that this width
The distribution over the invariant mass $M_{dat}$ calculated according to the mechanism in Fig. 2 in comparison with the data (○) [11]. Theoretical curves are normalized to the data is completely determined by the decay $D_{03} \to D_{12}\pi \to d\pi^0\pi^0$, which is the basis of the considered model, then in order to get agreement with the absolute value we should put $\Gamma(D_{03} \to d\sigma) = 8.5$ MeV. The contribution of the decay channel $D_{03} \to d\sigma \to d\pi^0\pi^0$ to the total width of the $D_{03}$ and the cross section of the reaction $pd \to pd\pi\pi$ will be estimated in forthcoming paper.

4 Conclusion

The mechanism of the reaction $pd \to pd\pi\pi$ depicted in Fig. 2 was qualitatively considered in [11]. Here we present some numerical results on the basis of this mechanism. The shape of the calculated distributions over invariant mass $M_{dat}$ is in a reasonable agreement with the data reflecting the typical ABC-effect behaviour. However, we found that this “ABC-type” shape is caused by the collinear kinematics of the performed experiment [11] and does not occur within the considered model for the case when scattering angle of the deuteron is in the full interval $\theta = 0 \div \pi$. We found also that the shape of the distribution over invariant mass $M_{intr}$ is in qualitative agreement with the data [11].

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References

[1] H. Clement, Prog. Part. Nucl. Phys. 93, 195 (2017)
[2] P. Adlarson et al. (WASA@COSY Collab.), Phys. Rev. Lett. 106, 242302 (2011)
[3] Y. Dong, F. Huang, P. Shen, Z. Zhang, Phys. Rev. C 94, 014003 (2016)
[4] A. Gal, H. Garzilazo, Phys. Rev. Lett. 111, 172301 (2013)
[5] A. Gal, H. Garzilazo, Nucl.Phys. A 928, 73 (2014)
[6] A. Gal, Phys. Lett. B 769, 436 (2017)
[7] J.A. Niskanen, Phys.Rev. C 95, 054002 (2017)
[8] N.E. Booth, A. Abashian, K.M. Crowe, Phys. Rev. Lett. 7, 35 (1961). Phys. Rev. Lett. 5, 258 (1960)
[9] M. Baskanov, H. Clement, T. Skorodko, Nucl. Phys. A 958, 129 (2017)
[10] M.N. Platonova, V.I. Kukulin, Phys. Rev. C 87, 025202 (2013)
[11] V. Komarov et al. (for ANKE@COSY Collab.), arxiv:1805.01493 [nucl-exp]
[12] Yu.N. Uzikov, in Proc. of Baldin ISHEPP XX “Relativistic Nuclear Physics and Quantum Chromodynamics”, Dubna, October 4-9, 2010 Eds. S.G. Bondarenko, V.V. Burov, A.I. Malakhov, E.B. Plekhanov (JINR, Dubna, 2011) 251
[13] M. Baskanov, H. Clement, T. Skorodko, Eur. Phys. J. A 51, 87 (2015)
[14] A. Gal, arxiv:1803.08788 [nucl-th]
[15] L. Alvarez-Ruso, E. Oset, E. Heranndez, Nucl.Phys. A 633, 519 (1998)
[16] M.N. Platonova, V.I. Kukulin, Nucl. Phys. A 946, 117 (2016)