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

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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 $D_{IJ} = D_{03}$ 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 Δ-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 the nucleon, $\Delta(1232)$-isobar and pion degrees of freedom, it is also possible to get a resonance state in the $\pi N\Delta$ system [4–6], with rather narrow width if one assumes excitation of the dibaryon resonance D_{12} in the $N\Delta$-interaction. 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 Δ's and, therefore, cannot be used for decay of the Δ-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

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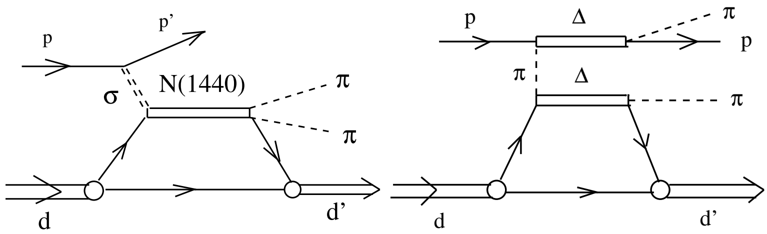

Figure 1. Mechanisms of the reaction $pd \to pd\pi\pi$ with the Roper (left) and $\Delta\Delta$ (right) excitation studied in [12]

ABC effect in the reaction $pn \to d\pi^0\pi^0$ were discussed in [9]. One possible mechanism of the reaction $pn \to d\pi^0\pi^0$ 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 $pd \to pd\pi\pi$ 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 $M_{\pi\pi}$.

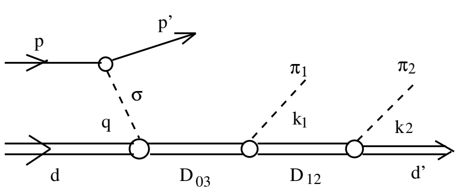

Figure 2. Two resonance mechanism of the reaction $pd \to pd\pi\pi$

Two mechanisms of this reaction involving excitation of the Roper resonance $N^*(1440)$ and two Δ-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 $pd \to pd\pi\pi$, 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 $pn \to d\pi^0\pi^0$ 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 σ-meson exchange between the proton and deuteron and apply it to the process $pd \to pd\pi\pi$ (Fig. 2). As it was found in [10], the ABC effect in the reaction $pn \to d\pi^0\pi^0$ can be explained if an additional decay mechanism is included, $D_{03} \to d\sigma \to d\pi^0\pi^0$, 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 $pn \to d\pi^0\pi^0$ 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:

$$M^{\lambda'_p\lambda'_d}_{\lambda_p\lambda_d}(pd \to pd\pi\pi) = M^{\lambda'_p}_{\lambda_p}(p \to p'\sigma)\frac{1}{p_\sigma{}^2 - m_\sigma{}^2 + im_\sigma\Gamma_\sigma}M^{\lambda'_d}_{\lambda_d}(\sigma d \to d\pi\pi), \quad (1)$$

where p_σ, m_σ, Γ_σ are the 4-momentum, mass, and the total width of the σ-meson, respectively; $\lambda_i(\lambda'_i)$ is the spin projection of the initial (final) particle i. The amplitude of the virtual process $p \to p\sigma$ is based on the phenomenological σNN interaction [15] and its spin averaged form $\overline{|M^{\lambda'_p}_{\lambda_p}(p \to p'\sigma)|^2}$ is given in [12].

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

$$M^{\lambda'_d}_{\lambda_d}(\sigma d \to d\pi\pi) = \sum_{\lambda_2,\lambda_3,\mu,m_1,m_2}\frac{F_{D_{03}\to d\sigma}F_{D_{03}\to D_{12}\pi_1}}{P^2_{D_{03}} - M^2_{D_{03}} + iM_{D_{03}}\Gamma_{D_{03}}}\frac{F_{D_{12}\to d\pi_2}}{P^2_{D_{12}} - M^2_{D_{12}} + iM_{D_{12}}\Gamma_{D_{12}}}$$
$$\times(1\lambda_d2\mu|3\lambda_3)\mathcal{Y}_{2\mu}(\hat{\mathbf{q}})(2\lambda_21m_1|3\lambda_3)\mathcal{Y}_{1m_1}(\hat{\mathbf{k}}_1)(1\lambda'_d1m_2|2\lambda_2)\mathcal{Y}_{1m_2}(\hat{\mathbf{k}}_2) + (\pi_1 \leftrightarrow \pi_2), \quad (2)$$

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; $\mathbf{q}$ is the 3-momentum of the initial deuteron in the c.m.s of the D_{03}, $\mathbf{k}_1$ is the 3-momentum of the pion π_1 in the c.m.s of D_{03}, and $\mathbf{k}_2$ is the 3-momentum of the pion π_2 in the c.m.s of the D_{12}. We use in Eq. (2) standard notations for the Clebsch-Gordan coefficients $(j_1m_1j_2m_2|JM)$ and spherical functions $\mathcal{Y}_{lm}(\hat{\mathbf{k}}) = k^lY_{lm}(\hat{\mathbf{k}})$. The orbital momenta in the vertices $D_{03} \to \pi D_{12}$ and $D_{12} \to d\pi$ are $l_1 = l_2 = 1$ and in the vertex $d + \sigma \to D_{03}$ is $l = 2$. The vertex factors F in Eq. (2) are defined as in [10]:

$$\frac{F_{D_{03}\to d\sigma}(q)}{M_{D_{03}}(q)} = \sqrt{\frac{8\pi\Gamma^{(l=2)}_{D_{03}\to d\sigma}(q)}{q^5}}, \quad \Gamma^{(l=2)}_{D_{03}\to d\sigma}(q) = \Gamma^{(l=2)}_{D_{03}\to d\sigma}\Big(\frac{q}{q_0}\Big)^5\Big(\frac{q_0^2 + \lambda^2_{d\sigma}}{q^2 + \lambda_{d\sigma}}\Big)^3, \quad (3)$$

$$\frac{F_{D_{03}\to D_{12}\pi_1}(k_1)}{M_{D_{12}\pi}(k_1)} = \sqrt{\frac{8\pi\Gamma^{(l=1)}_{D_{03}\to D_{12}\pi}(k_1)}{k_1^3}}, \quad \Gamma^{(l=1)}_{D_{03}\to D_{12}\pi}(k_1) = \Gamma^{(l=1)}_{D_{03}\to D_{12}\pi}\Big(\frac{k_1}{k_{10}}\Big)^3\Big(\frac{k_{10}^2 + \lambda^2_{D_{12}\pi}}{k_1^2 + \lambda_{D_{12}\pi}}\Big)^2,$$

$$\frac{F_{D_{12}\to d\pi_2}(k_2)}{M_{d\pi_2}(k_2)} = \sqrt{\frac{8\pi\Gamma^{(l=1)}_{D_{12}\to d\pi}(k_2)}{k_2^3}}, \quad \Gamma^{(l=1)}_{D_{12}\to d\pi}(k_1) = \Gamma^{(l=1)}_{D_{12}\to d\pi}\Big(\frac{k_2}{k_{20}}\Big)^3\Big(\frac{k_{20}^2 + \lambda^2_{d\pi}}{k_2^2 + \lambda_{d\pi}}\Big)^2.$$

Here $M^2_{d\pi\pi} = P^2_{D_{03}}$, $M^2_{d\pi} = P^2_{D_{12}}$, 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 σdD_{03}, $\pi D_{12}D_{03}$ and πdD_{12}, respectively, via the triangle function $\lambda(m_1^2, m_2^2, m_3^2)$: $q^2 = \lambda(p^2_\sigma, m^2_d, P^2_{D_{03}})/(4P^2_{D_{03}})$; $k_1^2 = \lambda(m^2_\pi, P^2_{D_{12}}, P^2_{D_{03}})/(4P^2_{D_{03}})$, $k_2^2 = \lambda(m^2_\pi, m^2_d, P^2_{D_{12}})/(4P^2_{D_{12}})$, where m_π and m_d are the masses of the π-meson and deuteron, respectively; k_{10} (k_{20}) is the value of the k_1 (k_2) at the resonance point $P^2_{D_{03}} = M^2_{D_{03}}$ ($P^2_{D_{12}} = M^2_{D_{12}}$), $q_0 = q(m^2_\sigma, m^2_d, M^2_{D_{03}})$.

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

$$d\sigma = \frac{C_T}{(2\pi)^8\,64\,p_is}\int\int\overline{|M^{\lambda'_p\lambda'_d}_{\lambda_p\lambda_d}(pd \to pd\pi\pi)|^2}\,k\,q'\,p_f\,d\Omega_{\mathbf{k}}d\Omega_{\mathbf{q}'}d\Omega_{\mathbf{p}_f}dM_{\pi\pi}dM_{d\pi\pi}. \quad (4)$$

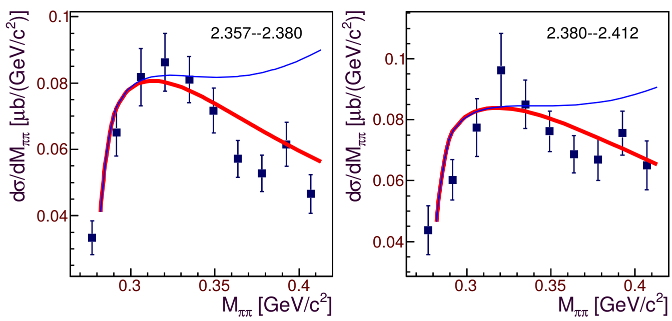

Figure 3. The distribution over the invariant mass of two final pions $M_{\pi\pi}$ in different intervals of the $d\pi\pi$ invariant mass (shown in pictures in GeV). The results of the model calculations (see text) are normalized to the data (■) [11] and shown by thick red lines for the real narrow interval of the deuteron scattering angle $\theta_{q'}$ in the c.m.s of the $d\pi\pi$ system occurred in the experiment [11] and by thin blue lines for the hypothetical full interval $\theta_{q'} = 0 \div \pi$

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, $\mathbf{k}$ is the pion momentum in the c.m.s of the $\pi\pi$ system, and $\mathbf{q}'$ 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 $M_{d\pi\pi}$ ($M_{\pi\pi}$) of the $d\pi\pi$ ($\pi\pi$) system. Integration intervals over variables $M_{\pi\pi}$, $cos\theta_{p_f}$ and $cos\theta_{q'}$ 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 $D_{03} \to d\pi^+\pi^-/D_{03} \to d\pi^0\pi^0$ is equal to 2 for unbroken isospin symmetry and 1.8 for the symmetry broken by the different masses of the π^+ and π^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, $\lambda_{\pi D_{12}} = 0.12$ GeV. The values $\Gamma^{(l=1)}_{D_{12}\to d\pi} = 10$ MeV, $\lambda_{d\sigma} = 0.18$ GeV and $\lambda_{d\pi} = 0.25$ GeV were obtained in [10]. The partial widths $\Gamma^{(l=2)}_{D_{03}\to d\sigma}$ and $\Gamma^{(l=1)}_{D_{03}\to D_{12}\pi}$ 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 $Y_{1m}(\theta, \phi)$ 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 $\theta_{q'}$ of the final deuteron, this effect disappears (thin blue lines in Fig. 3).

The absolute value of the cross section of the reaction $pd \to pd\pi\pi$ is proportional to the product of the partial widths $D_{03} \to d\sigma$, $D_{03} \to D_{12}\pi$, $D_{12} \to d\pi$. The experimental data on some partial widths are given in [13]. The partial widths $\Gamma(D_{12} \to d\pi)$ and $\Gamma(D_{12} \to NN)$ were estimated in [16] from the analysis of the cross section of the reaction $pp \to d\pi^+$. The partial width $\Gamma(D_{03} \to d\pi^0\pi^0)$ is about 10 MeV [13]. If we assume that this width

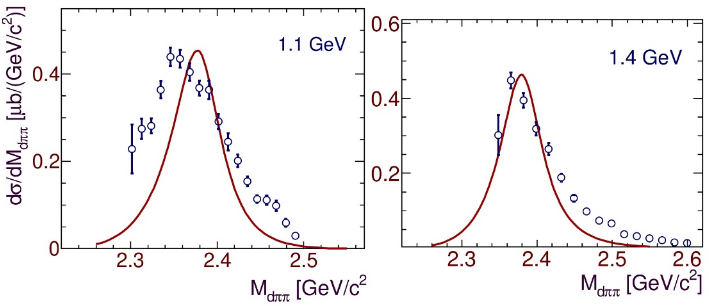

Figure 4. The distribution over the invariant mass $M_{d\pi\pi}$ calculated according to the mechanism in Fig. 2 in comparison with the data (∘) [11]. Theoretical curves are normalized to the data

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 $M_{\pi\pi}$ 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 $M_{d\pi\pi}$ is in qualitative agreement with the data [11].

Acknowledgment. One of the authors (Yu.U.) is thankful to M. Bashkanov, H. Clement, T. Skorodko and A. Gal for useful discussion. This work was supported in part by the program of the JINR-Kazakhstan cooperation.

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