I. INTRODUCTION: DIBARYONS ARE “TO BE OR NOT TO BE”?

Search for dibaryon resonances and their manifestations in hadronic and electromagnetic processes is a long-standing problem which takes its origin in the mid 1970ies (see the basic Refs. [1, 2] and also reviews [3, 4]). In that time, the first experimental indications appeared for existence of the number of dibaryon states. In particular, in elastic scattering of polarized protons for existence of the number of dibaryon states. In partic-

ular, in elastic scattering of polarized protons \( \vec{p} + \vec{p} \), the signals of a whole series of isovector dibaryons in \( ^1D_2 \), \( ^3F_3 \), \( ^1G_4 \), etc., partial waves were found [5–7]. Besides that, rather convincing though indirect indications for an isoscalar dibaryon with quantum numbers \( I(J^P) = 0(3^+) \) were found in measurements of the outgoing proton polarisation in the deuteron photodisintegration process \( \gamma d \to pn \) at energies \( E_{\gamma} \approx 400–600 \text{ MeV} \) [8–10].

It is worth emphasizing that the first theoretical prediction of dibaryon states based on SU(6) symmetry was done still in 1964 in the pioneering work of Dyson and Xuong [11], appeared only several months after Gell-Mann’s first publication on the quark model of hadrons [12]. In the following, a number of quark theoretical models [13–16] for dibaryons were proposed. At the same time, a series of theoretical works appeared (see, e.g., [17–20]) where dibaryon degrees of freedom (d.o.f.) in different hadronic processes were considered. In those works, the dibaryon parameters were adjusted ad hoc to describe the observables of a particular process under consideration, with no explicit relation to both microscopic quark models and the description for other types of hadronic processes, where the same dibaryon resonances should participate.

From the other hand, it was demonstrated [21–24] that the basic features of some hadronic processes, such as \( \pi d \to \pi d \), \( NN \leftrightarrow \pi d \), etc., where the dibaryon contributions were expected to be rather large, can be described within the framework of conventional meson-exchange mechanisms without any dibaryon contributions. Hence, it turned out to be very difficult to draw some definite conclusions about existence (or absence) of dibaryon resonances and their role in hadronic processes. The situation was worsened by the fact that, in spite of extensive searches, in that time (in 1980–90ies) no quite convincing experimental evidences for dibaryons were found [25]. As a result, the general interest to the problem faded away.

Recently, however, the situation around dibaryons began to change rapidly. A number of new inspiring results have appeared, that have led to some kind of renaissance in the area of dibaryon physics. One of the most important events in the field has been the prediction of a strange \( H \)-dibaryon in the lattice QCD calculations [26–27] and the following initiation of a big experimental program at JPARC [28] aimed at searching for the \( H \)-dibaryon. It is worth mentioning that unsuccessful experimental search for this dibaryon in previous years (since its first prediction by Jaffe [1]) was one of the reasons for scepticism against the existence of dibaryons (see, e.g., [29]).

The second not less important result is related to the non-strange dibaryons. It is the recent experimental finding of the isoscalar dibaryon resonance \( \mathcal{D}_{03}(2380) \) with \( I(J^P) = 0(3^+) \) (first predicted by Dyson and Xuong [11]) in the two-pion production reactions \( pn \to d\pi\pi \), \( dd \to ^4\text{He}\pi \) and \( pd \to ^3\text{He}\pi \) [30–34] and an explicit relation of this resonance to the well-known Abashian–Booth–Crowe (ABC) effect [35], i.e., an anomalous enhancement in the cross sections of these reactions just above the two-pion threshold. Although the interrelation between this dibaryon formation in the \( 2\pi \)-production reactions and the ABC effect was predicted already in an old paper [3], the reliable experimental data that confirmed this prediction have appeared only 30 years later. This has become
possible mainly due to considerable progress achieved in experimental technique (simultaneous registration of three and more particles in coincidence, measurements in full 4π geometry, etc.).

The remarkable features of the $D_{03}(2380)$ resonance are its mass, lying much (80 MeV) lower than the threshold of simultaneous excitation of two $\Delta$ isobars, and its rather narrow width $\Gamma_{D_{03}} \simeq 70$ MeV. Just these features made it possible to separate almost unambiguously the resonance signal from the background given by the conventional meson-exchange processes (mainly the $t$-channel $\Delta-\Delta$ excitation). It is generally not surprising that a resonance being short-range in nature is manifested most pronouncedly in the processes accompanied by large momentum transfers, where the contributions of peripheral meson-exchange processes are rather low. This seems the main reason for success in finding the $D_{03}$ resonance just in the two-pion production processes. Presently there are extensive searches also for other dibaryons proposed in [11], including states with higher isospins $I = 2$ and 3 [36]. The more challenging task, however, appears to be not only searching for some "exotic" dibaryon states in particular reactions, but revealing the interrelations between different dibaryons in connection with their manifestations in a whole range of processes as well as investigating the role of dibaryon d.o.f. in short-range $NN$ correlations and in the basic short-range nuclear force, in general.

We have suggested recently [37] that dibaryons can transform into each other through meson emission and absorption. In particular, it was shown that the essential role in the decay of the isoscalar resonance $D_{03}(2380)$ into $d\pi\pi$ channel may be played by an intermediate state $D_{12}(2150) + \pi$, where $D_{12}(2150)$ is an isovector dibaryon with $I(J^P) = 1(2^+)$ (also predicted in [11]). This idea was further developed in [38] within the framework of the rigorous three-body Faddeev calculations for the $\pi N\Delta$ system. If the dibaryon resonances really exist, such transitions between them seem to be quite natural. In fact, one may present a lot of examples of similar transitions in the traditional field of baryon resonances, such as the Roper resonance decay via an intermediate $\Delta$ isobar: $N^*(1440) \to \Delta + \pi \to N + \pi \pi$. However, the isovector dibaryon, and particularly $D_{12}(2150)$, have not yet become commonly accepted objects, though there is some important progress in this direction [39]. Despite the numerous indications for these dibaryons obtained from both experimental data and several independent partial-wave analyses (PWA) for the processes $pp \leftrightarrow pp$, $\pi^+d \leftrightarrow \pi^+d$ and $pp \leftrightarrow \pi^+d$ [10,11], their unambiguous identification is a rather difficult problem. In fact, the dibaryon $D_{12}(2150)$ lies very near to the $N\Delta$ threshold and has a width $\Gamma_{D_{12}} \simeq 100–120$ MeV close to that of the $\Delta$ isobar. Other isovector dibaryons, though lying higher than $N\Delta$-threshold, have smaller excitation strengths and larger widths. As a result, the isovector dibaryon resonances are highly uneasy to identify even in the well-researched reaction $pp \leftrightarrow \pi^+d$ where the large momentum transfers suppress the conventional peripheral processes [43]. Some new important information about these resonances could however still be obtained from the analysis of different hadronic processes where the same dibaryons can be excited.

In the present paper we tried to clarify the question of intermediate dibaryon contributions in hadronic processes, paying the most attention to one- and two-pion production in $NN$ collisions. The present work is focused on three main topics: (i) revealing the interconnections between different dibaryon resonances and investigating their possible mutual transformations; (ii) studying the relative role of the same dibaryons in different hadronic processes; (iii) clarifying the interrelation between the dibaryon resonance and background (meson-exchange) contributions.

The basic motivation of the present study was a general idea that the processes with large momentum transfers, e.g., $NN \to d\pi$, $NN \to d\pi\pi$, etc., proceed with a significant probability through generation of the intermediate resonances, such as dibaryons, owing to their longer lifetime compared to that of direct (non-resonance) processes. As the net effect of interaction is defined by an integral over the interaction time, it should be easier to transfer a large momentum in a resonance-like process than in a direct process without time delay.

From the other hand, the $NN$ collisions accompanied by a high momentum transfer must be very sensitive to the short-range components of the $NN$ force. Thus, a consistent description of such processes should apparently take into account the internal nucleon structure, because one deals here with the inter-nucleon distances $r_{NN} \lesssim 1$ fm, where the quark cores of two interacting nucleons are closely overlapped with each other. However, an explicit account of quark and gluon d.o.f. in description of hadronic processes like $pp \to d\pi^+$, $pn \to d\pi^+\pi^-$, etc., would lead to the huge complication of the whole picture.

At the same time, it was found [16,17] that the basic effects of the nucleon quark structure in the $NN$ interaction can be adequately described in terms of dibaryon rather than quark d.o.f. In such an approach, the $NN$-interaction $t$-matrix includes several resonance terms of the form $|\phi_0\rangle/(E - M_D^{(a)} + i\Gamma_D^{(a)}/2)$, where $M_D^{(a)}$ and $\Gamma_D^{(a)}$ are the mass and width of a dibaryon of the $a$-th kind, i.e., with a particular set of quantum numbers, and $|\phi_0\rangle$ is the dibaryon form factor, which represents the vertex function for the $a$-th resonance decay into $NN$, $NN\pi$, or $NN\pi\pi$ channels. Such a description does not require an explicit account of the quark-gluon d.o.f. and is directly related to the variables of the respective hadronic channel. As discussed above, rather strong indications of many dibaryon resonances were found by different experimental groups in the very numerous works (see reviews [3,4] and also recent papers [30,31]). Although the nature of these resonances is still a subject of debates [20], the fruitfulness of their introduction for an effective account of quark d.o.f. at short inter-nucleon
distances seems undoubtable.

In Sec. II the one-pion production process pp → dπ+ is analyzed from the traditional viewpoint and the problems in description of this process within the framework of the conventional meson-exchange approach are demonstrated. Such a detailed investigation is necessary for clarifying the interplay between the background (meson-exchange) and resonance (dibaryon) contributions. In Sec. III we explore the contribution of isovector dibaryons (mainly the D12(2150)) to the one-pion production processes. By using the realistic parameters for dibaryon resonances, we obtain a good description for the pp → dπ+ partial and total cross sections. We show further that the assumed values of dibaryon parameters do not contradict the empirical data for pp and π+ d elastic scattering. Sec. IV is devoted to the analysis of the different 2π-production processes in pn and pp collisions. The possibility of a consistent description for one- and two-pion production processes with inclusion of intermediate dibaryon resonances is demonstrated. In Sec. V we discuss the possible quark-cluster structure of dibaryons in connection with the observed strong differences between 2π production cross sections in pn and pp collisions in the GeV region. Finally, in Sec. VI we briefly summarize our conclusions.

II. CONVENTIONAL DESCRIPTION OF THE ONE-PION PRODUCTION REACTION NN → dπ: PROBLEMS AND SOLUTIONS

The basic one-pion production reaction NN → dπ has been the subject of very numerous experimental and theoretical studies since 1950ies [48]. The reaction was treated within the framework of phenomenological models [24, 49], the coupled-channels approach [22] and also the Faddeev-type multiple-scattering approach [23]. Thus it has long been revealed that the main features of the process at energies T_N = 400 - 800 MeV can be explained by excitation of an intermediate ΝΔ system. The important role is also played by interference of the NΔ mechanism with the one-nucleon-exchange (ONE) process. From the other hand, the final-state rescattering contributions were estimated to give no more than 20% of the total cross section without changing the basic qualitative features of the reaction [24]. However, a number of more sensitive polarization characteristics were not reproduced within the framework of conventional meson-exchange models [23, 24]. So, it was claimed [17] that excitation of the intermediate dibaryon resonances found in elastic pp scattering [3, 3] should be taken into account in the NN → dπ process.

On the other hand, since the process is accompanied by rather large momentum transfers (∆p > 350 MeV), the contribution of the conventional NΔ mechanism depends strongly on the short-range cut-off parameters in the πNN and πNΔ vertices [49]. Therefore, the proper choice of these parameters is crucial to determine the real contribution of the conventional mechanisms and the possible role of the intermediate dibaryon resonances. To our knowledge, this important problem, i.e., the relationship between the contributions of intermediate dibaryons and the values of the cut-off parameters Λ_{π,NN} and Λ_{π,NΔ}, has not been paid enough attention in the existing literature. However, clarification of this issue, as is shown below, plays a key role in the present study. Therefore, in this section, after describing the basic formalism for the reaction NN → dπ, we consider this problem in detail.

A. Basic formalism

Two basic conventional mechanisms of the reaction NN → dπ, i.e., one-nucleon exchange and excitation of the intermediate NΔ system by the t-channel pion exchange are shown in Fig. 1 (a) and (b), respectively. Further on, we will refer to these mechanisms as ONE and NΔ. An excitation of the intermediate Δ isobar through the ρ-meson exchange was also often considered in the literature [49], but such a mechanism contributes significantly only when choosing very high cut-off parameters in the meson-exchange form factors. Here, we choose the soft values for the cut-off parameters Λ < 1 GeV (reasons for this are given below), for which the contribution of the ρ-exchange mechanism is very small.

FIG. 1: Diagrams illustrating two basic conventional mechanisms for the reaction NN → dπ: one-nucleon exchange (a) and intermediate Δ-isobar excitation (b). The 4-momenta of the particles are shown in parentheses, and 3-momenta in pair center-of-mass systems are denoted by bold face.

1 The one-nucleon-exchange mechanism of the reaction NN → dπ is often referred to in the literature as an impulse approximation [24, 49]. However, we prefer to imply under the impulse approximation its standard meaning, i.e., single scattering in elastic processes.

2 In the present paper, we assume h = c = 1, so the particle masses and momenta are measured in energy units.
Relativistic helicity amplitudes corresponding to the diagrams depicted in Fig. 1 can be written as follows:

\[ \mathcal{M}_{\lambda_1, \lambda_2; \lambda d}^{(\text{ONE})} = I_a (2m)^2 \sum_{\lambda'} [\bar{v}(p_2, \lambda_2) G_{dNN}(\lambda_d) u(p', \lambda')] \times \frac{1}{P'^2 - m^2 - i0} \hat{U}(P', \lambda') F_{\pi NN}(\gamma^\mu q_\alpha \gamma_5 u(p_1, \lambda_1)), \]

(1)

\[ \mathcal{M}_{\lambda_1, \lambda_2; \lambda d}^{(\text{N}\Delta)} = I_b (2m)^2 \sum_{\lambda, \lambda'} \int \frac{id^4P}{(2\pi)^4} \frac{1}{k^2 - m^2 + i0} \times [\bar{v}(p_2, \lambda_2) F_{\pi NN}(\eta_2) \gamma^\mu k_\mu \gamma_5 v(P', \lambda')] \frac{1}{P'^2 - m^2 + i0} \times [\bar{v}(P, \lambda) G_{dNN}(\lambda_d) u(P', \lambda')] \frac{1}{P'^2 - m^2 + i0} \mathcal{M}_{\lambda', \lambda_1}^{(\pi N)}, \]

(2)

where \( \mathcal{M}_{\lambda', \lambda_1}^{(\pi N)} \) is the \( \pi N \)-scattering amplitude via an intermediate \( \Delta \) isobar:

\[ \mathcal{M}_{\lambda', \lambda_1}^{(\pi N)} = -4mW_\Delta \bar{u}(P', \lambda') F_{\pi NN}, \]

(3)

\[ \times \frac{q^\alpha T^{(3/2)}_{\alpha\beta} k^\beta}{W_\Delta^2 - M_\Delta^2 + iW_\Delta \Gamma_\Delta(W_\Delta)} F_{\pi NN} u(p_1, \lambda_1). \]

The \( G_{dNN} \) in Eqs. (1) and (2) stands for the relativistic deuteron vertex, \( I_a \) and \( I_b \) are the isospin coefficients and \( T^{(3/2)}_{\alpha\beta} \) in Eq. (3) denotes the projection operator for the intermediate \( \Delta \). The vertex form factors \( F_{\pi NN} \) and \( F_{\pi NN} \Delta \) will be defined below.

Since not only the reaction amplitudes \( \mathcal{M} \) defined in Eqs. (1)–(3), but also each elementary amplitude (enclosed in square brackets in Eqs. (1) and (2)) are relativistically invariant, it is convenient to calculate each elementary amplitude in its own c.m.s. Then the resulted expressions for the amplitudes can be cast into a non-relativistic form, up to a some energy-dependent factor of relativistic nature. The explicit form of this factor depends on the specific choice of the relativistic vertex and often cannot be determined unambiguously, hence we assume all such factors to be unity. Neglecting also the small effects of relativistic spin rotations for the intermediate nucleons, we can write the total amplitude in terms of nonrelativistic vertices depending on the relative 3-momenta in pairs of particles. Finally, applying the standard approximation of the spectator nucleon [49]

\[ \int \frac{id^4P}{(2\pi)^4} \frac{2m}{P'^2 - m^2 + i0} \bigg|_{P_0 = \sqrt{P'^2 + m^2}} \rightarrow \int \frac{d^3P}{(2\pi)^3} \]

(4)

and introducing the deuteron wavefunction (d.w.f.)

\[ \bar{v}(P) G_{dNN} u(P') \frac{\sqrt{2m}}{P'^2 - m^2 + i0} \rightarrow -\chi^i i\sigma_2 \Psi_d(\rho) \chi, \]

(5)

one gets the following expressions for the above amplitudes:

\[ \mathcal{M}_{\lambda_1, \lambda_2; \lambda d}^{(\text{ONE})} = -I_a (2m)^{3/2} \chi^i(\lambda_2) i\sigma_2 \]

\[ \times \Psi_d(\rho_d, \lambda_d) F_{\pi NN} (\eta_d)(\sigma \eta_d) \chi(\lambda_1), \]

(6)

\[ \mathcal{M}_{\lambda_1, \lambda_2; \lambda d}^{(\text{N}\Delta)} = -I_b (2m)^{1/2} \chi^i(\lambda_2) i\sigma_2 \]

\[ \times \int \frac{d^3P}{(2\pi)^3} \frac{F_{\pi NN}(\eta_2)(\sigma \eta_2)}{w_\Delta^2 - m_\Delta^2 + i0} \Psi_d(\rho_b, \lambda_d) \sqrt{\frac{\Gamma_\Delta(\lambda) \Gamma_\Delta(\lambda')}{\chi^3 \chi'^3}} \]

\[ \times 16\pi W_\Delta^2 (\chi \chi' + i\frac{\chi}{\chi'} \chi' \times \chi') \]

\[ \frac{W_\Delta - M_\Delta^2 + iW_\Delta \Gamma_\Delta(W_\Delta)}{W_\Delta} \chi(\lambda_1), \]

(7)

where \( w_\Delta^2 = k^2 \) and we made use of the relation of the \( \Delta \)-isobar width to the vertex function \( F_{\pi NN}\Delta \):

\[ \Gamma_\Delta(\lambda) = \frac{\chi^3 m}{6\pi W_\Delta} F_{\pi NN}(\lambda) \].

(8)

To calculate the spin structure of the amplitudes, it is convenient to write the d.w.f. in the form

\[ \Psi_d(\rho, \lambda_d) = \sigma \mathbf{E}(\rho, \lambda_d), \]

(9)

where we introduced the vector

\[ \mathbf{E}(\rho, \lambda_d) = u(\rho) \varepsilon(\lambda_d) + \frac{w(\rho)}{\sqrt{2}} \left( \varepsilon(\lambda_d) - \frac{3\rho(\varepsilon(\lambda_d))}{\rho^2} \right). \]

(10)

Here, \( \varepsilon(\lambda_d) \) is the standard deuteron polarization vector, and \( \rho \) and \( w \) are the \( S \) - and \( D \)-wave components of the d.w.f., normalized as \( \int d^3\rho (\rho^2 + w^2)/(2\pi)^3 = 1 \).

Although the vertices in Eqs. (6) and (7) are calculated non-relativistically, we still employ relativistic kinematics in calculations of the relative momenta, according to the minimal relativity principle. In fact, comparison of the results of non-relativistic [49] and fully relativistic [24] calculations for the ONE and \( \text{N}\Delta \) mechanisms shows that the account of relativistic effects as well as the deviation from the nucleon-spectator approximation give a correction of no more than 10–15%. Since the description of the \( NN \rightarrow d\pi^+ \) reaction in terms of two basic mechanisms only is initially approximate, the fully relativistic description of these mechanisms, requiring much more elaborated calculations, seems impractical at this stage. Furthermore, since the relativistic factors which we neglected here would increase the cross sections by 10–15% and the rescattering corrections would, on the contrary, decrease them by \( \approx 20\% \) [24], these two types of corrections would considerably cancel each other.

For definiteness, the reaction \( pp \rightarrow d\pi^+ \) will be considered further. Then the isospin coefficients are \( I_a = \sqrt{2} \).
and \( f_0 = 4\sqrt{2}/3 \). The helicity amplitudes must be antisymmetrized over the initial protons. Then they take the form\(^3\) \[ \mathcal{M}_{\lambda_1,\lambda_2;\lambda_3}(\theta) = \mathcal{M}_{\lambda_1,\lambda_2;\lambda_3}(\theta) + (-1)^{\lambda_3} \mathcal{M}_{\lambda_2,\lambda_1;\lambda_3}(\pi - \theta). \] (11)

Overall, there are 6 independent helicity amplitudes in the reaction \( pp \to d\pi^+ \):

\[
\begin{align*}
\Phi_1 &= \mathcal{M}_{\frac{1}{2},\frac{1}{2};0}^{(s)}, \quad \Phi_4 = \mathcal{M}_{\frac{1}{2},-\frac{1}{2};0}^{(s)}, \\
\Phi_2 &= \mathcal{M}_{\frac{1}{2},0;0}^{(s)}, \quad \Phi_5 = \mathcal{M}_{\frac{1}{2},-\frac{1}{2};0}^{(s)}, \\
\Phi_3 &= \mathcal{M}_{\frac{1}{2},\frac{1}{2};-1}^{(s)}, \quad \Phi_6 = \mathcal{M}_{\frac{1}{2},-\frac{1}{2};-1}^{(s)}. \quad (12)
\end{align*}
\]

The total cross section is expressed through the above six amplitudes as follows:

\[
\sigma(pp \to d\pi^+) = \frac{1}{64\pi s} \frac{q}{p} \sum_{i=1}^{6} |\Phi_i(x)|^2 \, dx, \tag{13}
\]

where \( p \) and \( q \) are the moduli of the proton and the pion c.m.s. momenta, respectively, and \( x = \cos(\theta) \).

For comparison of the theoretical results with the PWA data and for studying the contributions of the intermediate dibaryon resonances, it is convenient to deal with the partial-wave amplitudes, which are expressed through the helicity ones via the standard formulas given by Jacob and Wick \[51\]. We display here the explicit formulas for the amplitudes in two dominant partial waves \( ^1D_2P \) and \( ^3F_3D \) only:

\[
A(^1D_2P) = \frac{1}{2} \sqrt{\frac{3}{5}} \left( \Phi_1^{(2)} + \Phi_3^{(2)} \right) + \frac{1}{\sqrt{5}} \Phi_2^{(2)}, \tag{14}
\]

\[
A(^3F_3D) = -\frac{2}{\sqrt{7}} \Phi_4^{(3)} - \frac{1}{2\sqrt{7}} \Phi_5^{(3)}, \tag{15}
\]

where

\[
\Phi_i^{(J)} = \int_{-1}^{1} d\lambda_i \mathcal{A}_{\lambda_i-\lambda_2-\lambda_3}(x)\Phi_i(x) \, dx. \tag{16}
\]

The respective partial cross sections are

\[
\sigma(^{2S+1}L_JL^{\pi d}) = \frac{(2J+1) q}{64\pi s} \left| A(^{2S+1}L_JL^{\pi d}) \right|^2. \tag{17}
\]

### B. Parametrization of the vertex form factors: the cut-off problem

The main issue in the calculation of the amplitudes for the conventional processes, such as \( N\Delta \) mechanism shown in Fig. 1\( (b) \), is the parametrization of the meson-exchange vertex functions, in our case, the \( F_{\pi NN} \) and \( F_{\pi N\Delta} \), especially in the short-range (or high-momentum) region. In fact, one has currently no definite solution for the hard problem of the true short-range cut-off parameters in the above vertices, despite the very numerous works dedicated to this issue (see, e.g., \[51\] and references therein). Results of the different quark-model based calculations agree, in general, that the parameters in the meson-exchange vertices should be essentially soft (\( \Lambda < 1 \) GeV), but the precise values of these parameters are still unknown. In the present study, we have chosen the most simple vertex parametrization which follows directly from the basic principles of non-relativistic quantum mechanics combined with a minimal relativity principle. The advantages of such a choice are demonstrated below.

In the \( \pi N \) c.m.s., the vertex functions \( F_{\pi NN} \) and \( F_{\pi N\Delta} \) depend on the relative momentum of the pion and the nucleon. In its turn, the modulus of the relative momentum of two particles \( b \) and \( c \) produced in the decay of a particle \( a \) is a relativistically invariant quantity depending on invariant masses of all three particles:

\[
p_{bc}^2 = \frac{(w_a^2 - w_b^2 - w_c^2)^2 - 4w_a^2w_c^2}{4w_a^2}. \tag{18}
\]

Then, writing the vertex form factor as a function of \( p_{bc} \) makes it possible to describe the real and virtual particles in a unified manner.

When choosing a simple monopole parametrization for the above vertex functions, one has:

\[
F_{\pi NN}(p, \tilde{\Lambda}) = \frac{f}{m_\pi} \frac{p_a^2 + \tilde{\Lambda}^2}{p^2 + \tilde{\Lambda}^2}, \tag{19}
\]

\[
F_{\pi N\Delta}(p, \tilde{\Lambda}_s) = \frac{f_s}{m_\pi} \frac{p_0^2 + \tilde{\Lambda}_s^2}{p^2 + \tilde{\Lambda}_s^2}, \tag{20}
\]

where \( p^2 \) is a modulo squared of the \( \pi - N \) relative momentum (i.e., the pion momentum in the \( \pi N \) c.m.s.) and \( p_0^2 \) corresponds to the situation when all three particles are real, i.e., located on their mass shells. Then one gets the standard expression for the \( \Delta \to \pi N \) decay width (see Eq. 8):

\[
\Gamma_{\Delta}(p) = \Gamma_{\Delta} \left( \frac{M_{\Delta}}{W_{\Delta}} \right) \left( \frac{p}{p_0} \right)^3 \left( \frac{p_0^2 + \tilde{\Lambda}_s^2}{p^2 + \tilde{\Lambda}_s^2} \right)^2. \tag{21}
\]

The coupling constants in Eqs. (19)–(20) have been taken to be \( f = 0.97 \) and \( f_s = 2.17 \). In this case, one has \( f^2/4\pi = 0.075 \), and the above value for \( f_s \) was derived.

\[\text{3 The factor } 1/\sqrt{2} \text{ appearing in Eq. (A8) of Ref. 24 as well as the same factor for the } d-n-p \text{ isospin vertex are included here in the d.w.f. normalization.}\]
from the total width of the $\Delta$ isobar $\Gamma_\Delta = 117$ MeV as given by the Particle Data Group [52].

In case when only pion is off the mass shell, Eqs. (19)–(20) are reduced to the standard monopole form factors, depending on the pion invariant mass $w_\pi$ only (up to small terms proportional to $w_\pi^4$):

$$F_{\pi NN}(w_\pi; w_N = m, w_N = m) \approx \frac{f}{m_\pi} \frac{m_\pi^2 - \Lambda^2}{w_\pi^2 - \Lambda^2}, \quad (22)$$

$$F_{\pi N\Delta}(w_\pi; w_N = m, w_\Delta = M_\Delta) \approx \frac{f_\pi}{m_\pi} \frac{m_\pi^2 - \Lambda^*_\pi^2}{w_\pi^2 - \Lambda^*_\pi^2}, \quad (23)$$

where the cut-off parameters are related to the initial ones by

$$\Lambda^2 \simeq \tilde{\Lambda}^2, \quad (24)$$

$$\Lambda^*_\pi^2 \simeq \left(\tilde{\Lambda}^2 + \frac{(M_\Delta^2 - m_\pi^2)^2}{2M_\Delta^2}\right) / \left(\frac{M_\Delta^2 + m_\pi^2}{2M_\Delta^2}\right). \quad (25)$$

It should be noted here that a different parametrization for the phenomenological vertices of the type $F_{a \to bc}$ is often used in the literature. In this commonly used parametrization, the total vertex function is represented as a product of three independent functions, each depending on the one invariant mass only (see, e.g., [53]). This form of the vertices contains at least three independent parameters, some of which cannot be found from experimental data. Therefore, such a parametrization does not allow to establish a direct interconnection between the different processes involving the same particles on and off the mass shell. On the other hand, the vertex parametrization of the form $F(p_{bc}, \Lambda)$ with a single cut-off parameter $\Lambda$, used in the present work, is consistent with the basic principles of quantum mechanics and admits a straightforward off-shell continuation. The parameter $\Lambda$ in such a case can in general be found directly from experimental data.

Thus, the parameter $\tilde{\Lambda}_\pi$ in the $\pi N\Delta$ vertex can be found from empirical data on $\pi N$ elastic scattering. Fig. 2 shows the PWA (GW SAID) data [54] for the $\pi N$-scattering cross section in the $P_{33}$ partial wave and the results of calculations in the isobar model with a vertex form factor (20) for two values of the parameter $\tilde{\Lambda}_\pi$. We found that the best agreement between the theoretical calculation and the empirical data in a wide energy range is obtained by choosing the value $\tilde{\Lambda}_\pi = 0.3$ GeV. Then, using Eq. (23), we obtain the respective monopole parameter $\Lambda_\pi = 0.44$ GeV, which is indeed very soft.4

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4 We note in passing that a similar value $\tilde{\Lambda}_\pi \simeq 0.36/\sqrt{2} \simeq 0.26$ GeV (where we used the relation of the monopole cut-off parameter to the dipole one) was used in Ref. [54] to describe the $NN$-scattering phase shifts up to the energies $T_N = 2$ GeV consistently with $\pi N$ elastic scattering.

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FIG. 2: (Color online) The cross section of $\pi N$ elastic scattering in the $P_{33}$ partial wave. Solid and dashed lines show the calculations in the isobar model with the $\pi N\Delta$ vertex in the form (20) and cut-off parameters $\Lambda_\pi = 0.3$ and 0.5 GeV, respectively. Solid circles correspond to the PWA data (GW SAID, solution WI08 [54]).

It was argued in many theoretical studies that the cut-off parameter value in the $\pi N\Delta$ vertex (in monopole parametrization) should be substantially (100–300 MeV) less than that in the $\pi N N$ vertex (see, e.g., [51, 56, 57]). In the present study, we have taken the value $\Lambda \simeq \tilde{\Lambda} = 0.7$ GeV, which was used in a number of previous calculations of reactions such as $N N \to d\pi$ [24, 58]. This value of $\Lambda$ is consistent with the predictions of the lattice-QCD calculations [59, 60] (see also Ref. [61]). Thus, the monopole fits for the results obtained in [59] (lattice QCD with extrapolation to the physical pion mass) and [60] (extrapolation to the chiral limit) give $\Lambda = 0.75$ and 0.61 GeV, respectively. We emphasize here that the similar values $\Lambda = 0.65$–0.7 GeV were obtained in the fit of $NN$-scattering phase shifts and the deuteron properties within the dibaryon model for $NN$ interaction [40]. One should also note that relativistic quark models predict an even softer cut-off for the $\pi N N$ vertex function [61]. Unfortunately for the $\pi N\Delta$ form factor, we presently have no lattice-QCD predictions at the physical pion mass (or the respective extrapolation), and the available results at $m_\pi \simeq 300$ MeV [62] give too high cut-off parameters for both $\pi NN$ and $\pi N\Delta$ vertices. Therefore, one is forced to use phenomenological parametrizations for $F_{\pi N\Delta}$, like the one used in this work, trying to relate the parameters to experimental data wherever possible.

So, for the ratio of the cut-off parameters in the vertices $F_{\pi NN}$ and $F_{\pi N\Delta}$, we obtained the value $\Lambda_\pi/\Lambda \simeq 0.6$. Note that the same value was derived in [63] from comparison of the relativistic meson-exchange model calculations with experimental data for the process $NN \to$
It should be stressed here once again that the parametrization for the vertex functions $F_{\pi NN}$ and $F_{\pi N\Delta}$ which we adopt in the present study describes the real and virtual particles in a unified manner. Hence, it can be used for consistent description of processes involving on- and off-shell pions, i.e., $\pi N \rightarrow \pi N$, $NN \rightarrow \pi d$, elastic $NN$ scattering, etc., with realistic (soft) cut-off parameters in the meson-exchange vertices. It does not require introducing any additional parameters to account for the particles leaving their mass shells. Although this choice of the vertex parametrization is not unique, it seems to be the simplest and most natural.

It should be stressed that the cut-off parameters used here are much softer than those traditionally used in the realistic $NN$-potential models. For example, in the Bonn model [64], the minimal values, which still allow a good description of $NN$-scattering phase shifts up to $T_N = 350$ MeV, are $\Lambda \simeq \Lambda_* \simeq 1.3$ GeV. Such very high cut-off parameters apparently lead to increased meson-exchange contributions at small inter-nucleon distances. In many cases, however, the artificial strengthening of the meson-exchange processes can mimic somehow the contributions of short-range QCD mechanisms which involve the quark-meson structure of interacting nucleons. So, in this way, the $t$-channel meson-exchange mechanisms with artificially enhanced cut-off parameters can really give the correct behaviour of some observables. For example, as was shown in Ref. [67], an accurate description of the basic deuteron properties can be obtained in the simple meson-exchange model, which takes into account the one-pion exchange only without any cut-off, i.e., with $\Lambda = \infty$. One can suggest this continuity between peripheral meson-exchange and short-range QCD mechanisms to be a manifestation of a fundamental quark/hadron continuity principle.

On the other hand, from the fact that the vertex function $F_{\pi N\Delta}$ in $\pi N$ scattering should have $\Lambda_* \simeq 0.4$ GeV, while for the description of reactions like $NN \rightarrow d\pi$ one should take $\Lambda \simeq 0.6$ GeV (see below and also Ref. [58]), and at the same time the correct description of the deuteron properties and $NN$-scattering in S-waves requires $\Lambda_* \simeq 1.3$ GeV [64], it follows that the phenomenological approach based on ad hoc fitting the short-range cut-off parameters in the meson-exchange vertices to describe a specific process is not quite consistent, and probably contains some internal contradictions tightly related to the contributions of quark d.o.f. (see Ref. [68] for the detailed discussion). Instead, we could use the universal (essentially soft) cut-off parameters in meson-exchange mechanisms to describe different processes in a unified manner. Then the deviations from experimental data, which would inevitably arise in this situation, might be regarded as indications of some short-range QCD-based mechanisms, not taken into account in the conventional meson-exchange approach. In this case, the stronger the observed discrepancies are and, accordingly, the larger cut-off parameters are needed to describe the experimental data, the stronger the “hidden” quark d.o.f. manifest themselves in the process. We will return to this question in Sec. III, where the contributions of intermediate six-quark objects (dibaryons) will be considered from this viewpoint.

As was shown above, the parametrization of the vertices in the form (19)–(20) allows us to take into account the effects of any of the three particles going off the mass shell. The most noticeable effect due to presence of the off-shell nucleons is seen in the ONE process, where the nucleon after pion emission is strongly off-shell. Introducing the form factor $\pi_{NN}$ at $(w_N^*; w_\pi = m_\pi, w_N = m)$ in the vertex $F_{\pi NN'}$ ($N'$ being the nucleon after pion emission), we found that the ONE contribution is reduced by $\simeq 30\%$ in comparison with the use of a constant $\pi NN'$ vertex. It should be noted that just the same effect was obtained in [24], where the vertex $F_{\pi NN'}$ with the off-shell nucleon has been derived from the dispersion relations. This coincidence provides an additional argument in favor of the vertex parametrization employed in the present work. We also got a reduction of the $N\Delta$ mechanism (taken in the nucleon-spectator approximation) due to the nucleon $N'$ going off the mass shell, but this effect turned out to be less significant than in case of the ONE mechanism, and amounted to $10\%$ only.

C. Results and discussion

We calculated the cross sections for the one-pion production reaction $pp \rightarrow d\pi^+$ in the energy range $\sqrt{s} = 2.03$–2.27 GeV ($T_p \simeq 320$–860 MeV) using the above formalism. The results for the partial cross section in the dominant partial wave $^1D_2P$ are shown in Fig. 3 (solid line). As “experimental” data for comparison with theoretical calculations, we took the results of PWA (GW SAID, solution C500 [67]) for the inverse reaction $\pi^+d \rightarrow pp$. The cross sections of the two reactions are related as

$$\sigma(pp \rightarrow d\pi^+) = \frac{3}{2} \left( \frac{2}{p} \right)^2 \sigma(\pi^+d \rightarrow pp).$$

The advantage of the chosen PWA solution (C500) is that it was obtained in a combined analysis of the three interrelated processes $\pi^+d \rightarrow pp$, $pp \rightarrow pp$ and $\pi^+d \rightarrow \pi^+d$. The results of this PWA solution for the reaction $\pi^+d \rightarrow pp$ in the dominant partial waves $^1D_2, ^3F_0$, etc., are in good agreement with the older PWA results [68, 69].

Because of the high transferred momenta in the one-pion production process ($\Delta p > 350$ MeV), it can be expected that theoretical predictions will be sensitive to the model of the deuteron wave function (d.w.f.) used in calculations. To clarify this issue, we considered several models of d.w.f., and, in particular, the d.w.f. derived from the dibaryon model for $NN$ interaction [47]. Our study has shown that, although the ONE mechanism is indeed very sensitive to the choice of d.w.f., the effect of
using different d.w.f. models in the summed contribution of the ONE + NΔ mechanisms to the partial ($^1D_2P$) and total cross sections does not exceed 10%.

So, we found that the conventional ONE + NΔ mechanisms with the meson-exchange vertices parameterized in the form (19)–(20) using the parameters $Λ = 0.7$ and $Λ_∗ = 0.3$ GeV (corresponding to the monopole parameters $Λ = 0.7$ and $Λ_∗ = 0.44$ GeV) give about half the experimental cross section in the $^1D_2P$ partial wave and also about half the total cross section near their maximal values (at $\sqrt{s} \simeq 2.14$–2.16 GeV), with a theoretical peak shifted by 10–20 MeV to the right relatively to its experimental position. It is worth noting that quite similar results were obtained previously in the works of other authors [17,70].

On the other hand, due to the strong sensitivity of the results to the cut-off parameters in the vertex functions $F_{\pi NN}$ and, in particular, $F_{\pi NΔ}$, enhancing these parameter values may lead to a significant increase in the theoretical cross sections. To demonstrate the importance of this observation, we examined two ways of the parameter variation. First, we increased the value of the parameter $Λ_*$ in the $\pi NΔ$ vertex from 0.3 to 0.55 GeV. In this case, we were able to reproduce approximately the absolute value of both partial and total cross sections in the energy range considered. However, as we demonstrated above, the value $Λ_∗ = 0.55$ GeV is no longer appropriate to describe the empirical data on the elastic $\pi N$ scattering beyond the resonance peak (see Fig. 2).

The second way often used in the literature is changing the vertex parametrization itself, so that the degree of virtuality for each of the three particles is governed by its own cut-off parameter independent from other particles. In this case, the monopole form factors for the $\pi NN$ and $\pi NΔ$ vertices with off-shell pions (and an off-shell $Δ$) would be written as follows:

$$F_{\pi NN}^{(2)}(ω_π) = \frac{f_∗}{m_π} \frac{m_π^2 - Λ^2}{ω_π^2 - Λ^2},$$

$$F_{\pi NΔ}^{(2)}(W_Δ; ω_π) = \frac{f_∗}{m_π} \frac{m_π^2 + Λ_∗^2}{ω_π^2 + Λ_∗^2} \frac{m_π^2 - Λ^2}{ω_π^2 - Λ^2},$$

where $x_{on}$ is the magnitude of the on-shell $\pi - N$ relative momentum, i.e., at $ω_π = m$ and $ω_π = m_π$, thus dependent on $W_Δ$ only. In such a parametrization, the parameter $Λ_*$ can still be chosen as to describe the $\pi N$ elastic scattering and thus should be equal to 0.3 GeV. The pion virtuality is, however, controlled by an additional parameter $Λ_*$, which, in general, cannot be determined from experimental data and thus is fitted to a particular process (in our case, $pp \rightarrow d π^+$). The results of calculations for the partial and total cross sections within the ONE + NΔ model using the vertex parametrization (27)–(28) are also shown in Fig. 3. It turns out that the theoretical cross sections are approximately consistent in magnitude with the empirical data, when using $Λ_∗ = 0.6$ GeV.

![FIG. 3: (Color online) The partial cross section of the reaction $pp \rightarrow d π^+$ in the dominant wave $^1D_2P$ calculated within the ONE + NΔ model using the vertex parametrization (19)–(20) and parameter values $Λ = 0.7$ and $Λ_∗ = 0.3$ GeV, which correspond to the monopole parameters $Λ = 0.7$ and $Λ_∗ = 0.44$ GeV — see Eq. (27) (solid line). The results of calculations with the vertex form factors (27)–(28) at $Λ = 0.7$ and $Λ_∗ = 0.6$ GeV for the partial ($^1D_2P$) and total cross sections are shown by the dashed and dash-dotted lines, respectively. The open and filled circles correspond to the PWA data (GW SAID, solution C500 [52,67]) for the partial and total cross sections, respectively.](image-url)
mechanism of excitation of the intermediate dibaryon $D_{12}(2150)$ in the $^1D_2P$ partial wave seems to be very likely candidate here. Indeed, according to numerous predictions \[^{[11, 33, 42]}\], the mass of this dibaryon lies about 10–30 MeV below the $N\Delta$ threshold. In addition, although it was shown \[^{[24]}\], that the discrepancies for the total cross section could in principle be eliminated by taking into account the final-state rescattering contributions, significant disagreement with experimental data remains in the more sensitive spin-dependent observables, even after taking rescattering corrections (and also relativistic effects) into account. Particularly strong disagreement was revealed in the deuteron tensor analyzing powers \[^{[23, 24]}\]. We postpone the detailed investigation of the observables (including spin-dependent ones) in the reaction $pp \to d\pi^+$ for our next paper. Here, we would just like to show that a consistent description of one-pion production by the conventional meson-exchange mechanisms encounters serious difficulties, including those which cannot be eliminated by fitting the cut-off parameters in the vertex form factors. It is important to note that the similar conclusion was made in a number of previous works on the one-pion production reactions \[^{[17, 24]}\].

Thus, in this section we have demonstrated a number of problems faced by the conventional meson-exchange models in description of hadronic processes with high momentum transfers, in particular, of one-pion production. The main difficulty lies in the strong sensitivity to the short-range cut-off parameters in the vertices of meson emission and absorption. It is rather obvious that, until these parameters are accurately determined from the fundamental theory, one will not be able to reveal the real degree of discrepancy between the traditional meson-exchange model calculations and experimental data. Nevertheless, it appears to be a general trend that describing the processes involving two nucleons requires higher cut-off parameters in the meson-exchange vertices than the processes involving just one nucleon. Hence, instead of increasing the cut-off parameters \textit{ad hoc} to describe the one-pion production, one can try to find the missing contributions by inclusion of the resonance mechanisms based on the assumption of the intermediate dibaryon formation.

### III. INCLUSION OF INTERMEDIATE (ISOVECTOR) DIBARYONS IN ONE-PION PRODUCTION AND ELASTIC SCATTERING

#### A. Reaction $pp \to d\pi^+$ with intermediate dibaryons

Let us now consider how the partial cross section of the reaction $pp \to d\pi^+$ in the dominant $^1D_2P$ wave changes, if one adds to the background amplitude determined by the $N + N\Delta$ mechanisms (see Eq. \[^{[14]}\]) the resonance amplitude corresponding to excitation of the intermediate dibaryon $D_{12}(2150)$. A diagram illustrating such a resonance process is shown in Fig. \[^{[5]}\]. The respective partial-wave amplitude has the form

$$A^{(D)}(^1D_2P) = -\frac{8\pi s}{\sqrt{pp}} \frac{\sqrt{2\Gamma_{D_{12} \to pp}(s)\Gamma_{D_{12} \to \pi d(s)}}}{s - M_{D_{12}}^2 + i\sqrt{s\Gamma_{D_{12}}(s)}}. \quad (29)$$

The factor 2 before the partial width $\Gamma_{D_{12} \to pp}$ is introduced to account for the identical particles in the initial state.

To calculate the contribution of an intermediate dibaryon to a particular process, one has to fix the dibaryon parameters somehow. It should be noted however that the parameters of dibaryon resonances and especially their partial widths have been known with large uncertainties. Therefore, the vast majority of phenomenological studies of dibaryon contributions to hadronic processes carried out in 1980ies (see, e.g., \[^{[17, 18, 20]}\]) included \textit{ad hoc} fitting the parameters of dibaryon resonances to a particular process in question. In fact, the explicit dibaryon contributions to the process $pp \to d\pi^+$ were considered in the only one work \[^{[17]}\], where the parameters of six hypothetical dibaryons were simultaneously fitted to describe the experimental data. So, it was highly uneasy to draw some reliable conclusions about the real contribution of intermediate dibaryons to this process. Hence, as the main goal of the present work is to give an objective estimate for contributions of dibaryon resonances to the one- and two-pion production reactions, we would like to avoid such \textit{ad hoc} fitting here. Instead, we preferred to take reasonable values for the parameters of dibaryon resonances from existing literature.
or from the clear physical considerations, and then test
the sensitivity of the obtained results to the parameter
variation. Presently, quite reliable parameter estimates
are found in the literature at least for the most reli-
ably established dibaryons $D_{12}(2150)$ and $D_{03}(2380)$.

FIG. 5: Diagram illustrating the excitation of an intermediate
dibaryon resonance in the reaction $NN \to d\pi$.

For the dibaryon $D_{12}$, we first fixed (up to $\pm 10$ MeV)
its mass and total width to be $M_{D_{12}} = 2.15$ GeV and
$\Gamma_{D_{12}} = 110$ MeV. This choice was based on the PWA
data \[40, 42\] and also on the results of the recent Faddeev
calculations for the $\pi NN$ system \[39\]. For parametriza-
tion of the energy dependence of the total resonance
width, we took the form $\Gamma_{D_{12}}(s) = \Gamma_{D_{12}\to \pi d}(s)/R_{\pi d}$,
where $R_{\pi d} = \Gamma_{D_{12}\to \pi d}/\Gamma_{D_{12}}$ is the branching ratio for
the $D_{12} \to \pi d$ decay mode at the resonance point. In
other words, we assumed that the total width of the $D_{12}$
dibaryon is proportional to its partial decay width into
the $\pi d$ channel. This choice was based on the fact that
the decay $D_{12} \to \pi NN$ has the same threshold behaviour
and the same dynamical mechanism in its origin as the
decay $D_{12} \to \pi d$, and the partial width $\Gamma_{D_{12}\to NN}$, ac-
cording to a number of estimates \[3, 42\], is only about
10\% of the total dibaryon width. Although the final
$\pi NN$ channel has a different phase-space volume than
the $\pi d$ channel, however, in view of relatively weak in-
fluence of the energy dependence of the total resonance
width on final results, we neglect this difference in the
present calculation.

Further, for the partial width $\Gamma_{D_{12}\to \pi d}$ we employed
essentially the same parametrization as for the $\Delta$-isobar
width $\Gamma_{\Delta\to \pi N}$ (up to a factor $M/W$ which is almost neg-
ligible for the dibaryon in the considered energy region):

$$\Gamma_{D_{12}\to \pi d}(q) = \Gamma_{D_{12}\to \pi d}(q_0) \left(\frac{q}{q_0}\right)^3 \left(\frac{q_0^2 + \Lambda_{\pi d}^2}{q^2 + \Lambda_{\pi d}^2}\right)^2,$$  \hspace{0.5cm} (30)

where $q_0$ is a value of the $\pi d$ relative momentum $q$ at the
energy $\sqrt{s} = M_{D_{12}} = 2.15$ GeV and $\Lambda_{\pi d} = \Lambda_{\Delta} = 0.3$ GeV
(cf. Eq. (21)). Given the fact that the basic hadronic component of the dibaryon $D_{12}$ is $N + \Delta$ \[39\], one may
assume that the mechanism of the dibaryon decay at the
quark level is essentially the same as that of the $\Delta$ decay,
so the above choice seems to be quite natural. For the
vertex $D_{12} \to NN$, we used the Gaussian form factor
derived on the basis of the quark shell model \[40\]. In
the work \[40\], a fit was performed for the $NN$-scattering
phase shifts up to the energies $T_N = 600$ MeV, within
the framework of the dibaryon model for $NN$ interac-
tion. In its simplest form, the model included pion ex-
change at large $NN$ distances and intermediate dibaryon
($D$) formation at small distances. The authors \[40\] found
the $D \to NN$ vertex form factors in various $NN$ partial
waves in the form of projections of the six-quark wave
functions onto the $NN$ channel. In the quark shell model,
such projections have the form of the harmonic oscillator
wave functions. So, from the fit of the $NN$ phase shift in the $^1D_2$ partial wave, the Gaussian (oscillator)
form factor for the $D_{12} \to NN$ vertex was obtained with
a scale parameter $\alpha = 0.25$ GeV. In the present work,
we took just this value as a first estimate.\(^5\) Thus, for
the incoming width $D_{12} \to NN$, we used the following
parametrization:

$$\Gamma_{D_{12}\to NN}(p) = \Gamma_{D_{12}\to NN}\left(\frac{p}{p_0}\right)^5 \exp\left(-\frac{p^2 - p_0^2}{\alpha^2}\right),$$  \hspace{0.5cm} (31)

where $p_0$ is a value of the $NN$ relative momentum $p$ at
$\sqrt{s} = 2.15$ GeV.

As was mentioned above, the partial width $\Gamma_{D_{12}\to NN}$ is
only $\approx 10\%$ of the total width $\Gamma_{D_{12}}$, so it is reasonable
to assume $\Gamma_{D_{12}\to NN} = 10$ MeV. For the width $\Gamma_{D_{12}\to \pi d}$,
there are several estimates in the literature, but the most
plausible one appears to be $\Gamma_{D_{12}\to \pi d} \lesssim 0.1 \Gamma_{D_{12}}$, ob-
tained independently in a number of works \[19, 21\]. It
seems unlikely that the decay width into the $\pi d$ channel
is less than the one into $NN$ the channel, thus, for an
estimate, we took $\Gamma_{D_{12}\to \pi d} \approx \Gamma_{D_{12}\to NN} = 10$ MeV.

Now it remains to determine the relative phase $\varphi_{12}$ be-
tween the resonance amplitude of the $D_{12}$ excitation and
the background amplitude given by $ONE + N\Delta$ mech-
nisms. Since we found the background processes to give
a strong underestimation of the $pp \to d\pi^+$ cross section
(see Fig. 3), it is natural first to consider the case
$\varphi_{12} = 0$, corresponding to constructive interference be-
tween the resonance and background contributions. In
fact, it turns out that for the above choice of dibaryon
parameters, the phase $\varphi_{12} \simeq 0$ gives the best des-
cription of the data (from the best fit to PWA data we have got
a value $\varphi_{12} = 0.04$). Thus, if the dibaryon mechanism
really makes a significant contribution to the reaction
$NN \to d\pi$ and its parameters are close to those we used
in the present study, the resonance amplitude should in-
derfer with the background one constructively.

The results of calculation for the $pp \to d\pi^+$ partial cross section in the $^1D_2P$ wave with the above fixed
dibaryon parameters (summarized in set A of Table 1) and
the relative resonance/background phase $\varphi_{12} = 0$
are shown in Fig. 6 by thick solid line. We see that the
theoretical line is in very good agreement with the PWA
data at all energies from threshold up to $\sqrt{s} \simeq 2.3$ GeV.
It is important to emphasize that this result was obtained

\footnote{One should bear in mind that this value may be changed slightly,
when one takes as a background to the dibaryon mechanism not
only pion exchange with intermediate nucleon, but also pion ex-
change with intermediate $\Delta$ excitation.}
without any fit of free parameters for both interfering amplitudes, i.e., the resonance and background ones.

At the same time, we found that already a small change in the basic dibaryon parameters is sufficient to describe the partial $^1D_2P$ cross section almost perfectly (i.e., in full agreement with the PWA data), with the same relative phase between the resonance and background amplitudes $\varphi_{12} = 0$. These slightly modified parameters are presented in set B of Table I. In fact, to accurately describe the partial cross section near the resonance peak, one needs only to increase the dibaryon mass by 5 MeV, while the modification of other parameters improves mainly the description of the data at higher energies. The result of calculations with such slightly modified parameters is shown in Fig. 6 by thin solid line.

![Figure 6](https://example.com/figure6.png)

**FIG. 6:** (Color online) Partial cross section of the reaction $pp \rightarrow d\pi^+$ in the $^1D_2P$ wave. The results of calculation including the background (ONE + $N\Delta$) mechanisms and an intermediate dibaryon excitation with the parameter set A (see Table I), i.e., with no fit, is shown by thick solid line. The individual contributions of the dibaryon excitation (dashed line) and background processes (dash-dotted line) are also shown. The dotted line corresponds to the calculation with a reduced parameter $\Lambda_{sd} = 0.15$ GeV. The thin solid line shows the results obtained with slightly modified parameters of the dibaryon mechanism (see Table I, set B). Open circles correspond to the PWA data (GW SAID, solution C500 [54, 67]).

Furthermore, we found that the sensitivity of the results to the dibaryon mass and width is stronger than to the cut-off parameters in partial widths. However, the deviation of the latter parameters from the initially adopted values leads to worsening (though not considerable) the description of the PWA data. For illustration, we have shown in Fig. 7 also the result of the calculation with the reduced value $\Lambda_{sd} = 0.15$ GeV (this value corresponds to an assumption of a constant partial width near the resonance point). Therefore, an accurate description of the data requires “fine tuning” of the model parameters. Given this fact, it may seem surprising that, by choosing the parameters from the independent sources and making no actual fit, we have got a very good agreement with empirical data. On the other hand, if the parameter values used here are close to the real ones, then this result becomes quite natural.

![Figure 7](https://example.com/figure7.png)

**FIG. 7:** (Color online) Total cross section of the reaction $pp \rightarrow d\pi^+$ with account of dibaryon $D_{12}$ formation in the partial wave $^1D_2P$ (thin solid line), as well as with two dibaryon resonances in the partial waves $^1D_2P$ and $^3F_3D$ included (thick solid line) in comparison with experimental data [71] (open squares) and the PWA (GW SAID) data (filled circles). The individual contributions of the dibaryon $D_{12}$ excitation mechanism (dashed line), the background processes ONE (dotted line) and $N\Delta$ (dash-dot-dotted line), and the summed contribution of the two background processes (dash-dotted line) are also shown.

It is known however that other isovector dibaryon res-
on elastic pion production are consistent with experimental data.

Before that, however, it is important to check reactions at intermediate energies from this production. Below, in Sec. IV, we consider the respective energies are even smaller than in one-pion production.

It seems hardly possible even in a rigorous multiple-scattering approach, when keeping in mind the vertex contributions of this fact in the literature (see, e.g., [73, 74], and also [76, 77]). However, in this paper, we restrict our analysis to the energy dependence of the partial and total cross sections only.

First of all, let us consider the pure contribution of the dibaryon $D_{12}$ excitation to the cross sections of $pp$ and $\pi^+d$ elastic scattering in partial waves $^1D_2$ and $^3P_2$, respectively. The $^1D_2$ partial-wave amplitude for $pp$ elastic scattering via the intermediate dibaryon $D_{12}$ has the form:

$$A_{pp}^{(1D_2)} = -\frac{8\pi s}{p} \frac{\sqrt{2\Gamma_{D_{12}\rightarrow pp}(s)}}{s - M_{D_{12}}^2 + i\sqrt{8\Gamma_{D_{12}}}(s)}$$

and the respective cross section is

$$\sigma_{pp}^{(1D_2)} = \frac{5}{64\pi s} A_{pp}^{(1D_2)}.$$  

Similarly, for the $^3P_2$ partial-wave amplitude and cross section in $\pi d$ elastic scattering one gets:

$$A_{\pi d}^{(3P_2)} = \frac{8\pi s}{q} \frac{\Gamma_{D_{12}\rightarrow \pi d}(s)}{s - M_{D_{12}}^2 + i\sqrt{8\Gamma_{D_{12}}}(s)}$$

and

$$\sigma_{\pi d}^{(3P_2)} = \frac{5}{48\pi s} A_{\pi d}^{(3P_2)}.$$  

Fig. S(a) shows that the dibaryon contribution to the $^1D_2$ partial cross section of elastic $pp$ scattering is $\simeq 25\%$ at energies near the resonance peak. However, as the contribution of the $^1D_2$ partial wave itself is only 10% of the total elastic $pp$ cross section, the $D_{12}$ dibaryon contribution to the total elastic cross section will be 2.5% only. It is interesting to note that the qualitative behavior of the dibaryon contribution agrees well with the behavior of the empirical $pp$ cross section in the $^1D_2$ partial wave. This is not unexpected, since we used for the $D_{12} \rightarrow NN$ vertex the Gaussian form factor obtained.

## Table I: Parameters of dibaryon resonance $D_{12}$ used in calculations of the one-pion production reaction $pp \rightarrow d\pi^+$.

| Set A (initial) | $M_{D_{12}}$ [MeV] | $\Gamma_{D_{12}}$ [MeV] | $\Gamma_{D_{12}\rightarrow pp}$ [MeV] | $\alpha$ [GeV] | $\Gamma_{D_{12}\rightarrow \pi d}$ [MeV] | $\Lambda_{\pi d}$ [GeV] |
|----------------|---------------------|------------------------|-----------------------------|-------------|-----------------------------|---------------|
| Set B (modified) | 2155                | 103                    | 10                          | 0.25        | 10                          | 8.4           | 0.25        |
from fitting the $^1D_2$ $NN$-scattering phase shift within the dibaryon model [46]. On the other hand, it is known that the description of this phase shift within the framework of conventional meson-exchange models faces a number of problems. In particular, it requires the introduction of phenomenological $L$-dependent terms in the $NN$ potential (see, e.g., [28]). Looking at Fig. 8 (a), one may suppose that, when adding the dibaryon contribution to a relatively smooth background given by meson-exchange mechanisms (with soft form factors), one will obtain qualitatively correct behavior of the $pp$-scattering cross section in the $^1D_2$ partial wave.

Fig. 8 (b) shows the partial cross section of elastic $\pi^+d$ scattering in the $^3P_2$ wave. An analysis of just this reaction in its time put the existence of isovector dibaryon resonances under question, when it became clear that the main features of experimental data can be explained in terms of the so-called “pseudoresonances”, appearing due to an intermediate $N + \Delta$ excitation [21]. The estimate for the dibaryon partial width $\Gamma_{D_{12} \to \pi d} \lesssim 0.1 \Gamma_{D_{12}}$ used in the present work was also obtained from the analysis of elastic $\pi^+d$ scattering [13, 21]. Our results confirm that the dibaryon contribution (with the same parameters as were used to describe one-pion production) to elastic $\pi^+d$ scattering even in the $^3P_2$ partial wave is indeed very small ($\simeq 5\%$). Further, since the $^3P_2$ partial wave gives about half total elastic $\pi^+d$ cross section near its peak, we obtain the dibaryon contribution to the total elastic $\pi^+d$ cross section to be about $2.5\%$ only, similarly to the case of $pp$ elastic scattering.

We calculated also the contribution of the standard single $\pi^+N$-scattering mechanism via an intermediate $\Delta$-isobar excitation to the partial and total elastic $\pi^+d$ cross sections. It is important to stress here that this mechanism, unlike the similar mechanisms of the intermediate $\Delta$ excitation in the $pp \to \pi^+d$ reaction and in $pp$ elastic scattering, is very weakly dependent on the cut-off parameter in the $\pi N\Delta$ vertex, because such vertices here contain the real pions only, and presence of virtual nucleons produces a very small effect on the cross sections.

The single-scattering amplitude in the nucleonspectator approximation (see Eq. (2)) is written as follows:

$$
\mathcal{M}^{(SS)}_{\lambda_d, \lambda_a} = -\frac{4}{3} \text{Sp} \int \frac{d^3p}{(2\pi)^3} \Psi_d(\rho_b, \lambda_d) \sqrt{\frac{\Gamma_{\Delta}(\kappa)\Gamma_{\Delta}(\kappa')}{\kappa^3\kappa'^3}} \times \frac{16\pi W_\Delta^2 (\kappa\kappa' + \frac{3}{2} \kappa \times \kappa')}{W_\Delta^2 - M_\Delta^2 + iW_\Delta \Gamma_{\Delta}(W_\Delta)} \Psi_d(\eta_b, \lambda_d),
$$

(36)

where the momenta are denoted as in Fig. 1 (b) (with the nucleon 1 and the virtual pion interchanged and the nucleon 2 replaced by the incoming deuteron) and the d.w.f. $\Psi_d$ is given by Eqs. (9)–(10). There are four independent

**FIG. 8:** (Color online) Cross sections for $pp$ (a) and $\pi^+d$ (b) elastic scattering. The dashed lines correspond to contributions of the intermediate dibaryon $D_{12}$ excitation. The open circles show the PWA (GW SAID [54]) data for the cross sections in $pp$ $^1D_2$ (solution SP07) and $\pi^+d$ $^3P_2$ (solution C500) partial waves, and the filled circles show the respective data for the total elastic cross sections. The PWA data for the $pp$ total elastic cross section are multiplied by a factor 0.2. For $\pi^+d$ scattering, the dominant contributions of the single $\pi^+N$-scattering mechanism to the partial $^3P_2$ (dot-dashed line) and the total elastic (solid line) cross sections are also shown. The shaded area corresponds to the total elastic $\pi^+d$ cross section resulting from the coherent superposition of the single scattering and dibaryon excitation mechanisms with an arbitrary relative phase.
helicity amplitudes in $\pi d$ elastic scattering:

$$\Phi_1 = M_{1,1}, \quad \Phi_2 = M_{1,0},$$

$$\Phi_3 = M_{1,-1}, \quad \Phi_4 = M_{0,0}. \quad (37)$$

Then one has for the total cross section

$$\sigma(\pi^+ d) = \frac{1}{96\pi s} \int_{-1}^{1} \left[ 2\left( |\Phi_1(x)|^2 + |\Phi_3(x)|^2 \right) + 4 |\Phi_2(x)|^2 + |\Phi_4(x)|^2 \right] dx, \quad x = \cos(\theta). \quad (38)$$

The amplitude in the $^3P_2$ partial wave is expressed through the helicity amplitudes as

$$A(^3P_2) = \frac{3}{10} \left( \Phi^{(2)}_1 + \Phi^{(2)}_3 \right) + \frac{2\sqrt{3}}{5} \Phi^{(2)}_2 + \frac{1}{5} \Phi^{(2)}_4, \quad (39)$$

where

$$\Phi^{(J)}_i = \int_{-1}^{1} d\lambda_{\lambda_\lambda}(x) \Phi_i(x) dx. \quad (40)$$

Our calculations have shown, in agreement with results of many previous works \cite{16, 21, 79}, that the single-scattering mechanism gives the by far dominating contribution to the $\pi^+ d$ elastic cross sections, both partial and total. We found also that possible interference between the dibaryon and single-scattering contributions can give a scatter $\pm12\%$ (depending on a relative phase) in the total elastic $\pi^+ d$ cross section, while the cross section shape, after adding the dibaryon contribution, remains practically unchanged (see Fig. 8(b)). One should further take into account that the contribution of multiple scattering processes to the elastic $\pi^+ d$ cross section is $\simeq 20\%$ \cite{80}, which is significantly higher than that of the dibaryon mechanism. As a result, the effect of intermediate dibaryon excitation appears to be hardly visible in the total elastic cross sections of $pp$ and $\pi^+ d$ scattering.

Thus, one can conclude from the above analysis that the model which includes the background (or pseudoresonance) meson-exchange processes and the intermediate dibaryon excitation mechanisms with reasonable parameters allows a good description of the one-pion production reaction $NN \rightarrow d\pi$ in a wide energy range and at the same time does not contradict the empirical data for elastic $NN$ and $\pi d$ scattering. One should however bear in mind the strong parameter dependence of such a model description, especially in the background $t$-channel mechanisms. In the next section we consider more clear manifestations of intermediate dibaryon resonances in the two-pion production processes, where the conventional meson-exchange contributions are expected to be smaller than those in one-pion production, due to the higher momentum transfers.

IV. DIBARYON RESONANCES IN TWO-PION PRODUCTION

A. Reaction $pn \rightarrow d(\pi\pi)_0$: isoscalar/isovector transition

In reactions of two-pion production, where the initial $NN$ pair merges into the final deuteron, there are two possible assignments for the total isospin $I = 1$ and 0. The most interesting case is a purely isoscalar process $pn \rightarrow d(\pi\pi)_{I=0}$, where the famous ABC effect \cite{35}, i.e., a strong enhancement in the yield of pion pairs near the $2\pi$ threshold, was observed \cite{30} (see also the older inclusive experiment \cite{81}). In recent works of the CELSIUS/WASA and then WASA@COSY Collaborations \cite{30, 31} the ABC effect was unambiguously associated with generation of a dibaryon resonance $D_{03}(2380)$ with $I(J^P) = 0(3^+)$, originally predicted by Dyson and Xuong \cite{11} and then studied in many theoretical and experimental works (see, e.g., \cite{82, 83}). In fact, it is the only isoscalar dibaryon resonance (except for the deuteron \cite{11}) firmly established for today. The authors \cite{31} found that the total cross section of the $2\pi$-production reaction $pn \rightarrow d\pi^0\pi^0$ in the energy range $T_p = 1–1.2$ GeV is predominantly determined by excitation of the intermediate $D_{03}$ resonance, while the contribution of background processes (mainly excitation of an intermediate $\Delta\Delta$ state via a $t$-channel meson exchange \cite{84}) is relatively small and does not exceed 10% near the cross section maximum (at $\sqrt{s} = 2.38$ GeV or $T_p = 1.14$ GeV). Therefore, the calculations of the $2\pi$-production reactions in the isoscalar $NN$ channel based on $D_{03}$-resonance excitation only (i.e., without inclusion of the $t$-channel background processes) can be regarded as a good approximation, at least near the resonance peak.

In our previous work \cite{37}, we considered two decay modes for the resonance $D_{03}(2380)$ into the $d\pi\pi$ channel, which follow directly from the dibaryon model for $NN$ interaction \cite{80}: (i) through emission of a light scalar $\sigma$ and

\footnote{We use here the same letters to denote the helicity and partial-wave amplitudes as for the $pp \rightarrow d\pi^+$ process since this should not lead to confusion.}
meson and (ii) via an intermediate state $D_{12}(2150) + \pi$. In other words, we assumed that while the isovector dibaryons cannot be excited directly in the isoscalar $NN$ collisions, these dibaryons may be produced in the intermediate subsystem $\pi NN$, i.e., after the one-pion emission. Now we can verify this assumption independently, comparing the parameters of the isovector dibaryon $D_{12}$ in one- and two-pion production processes. We actually used in the present paper the same values for the $D_{12}$ mass and width, as in the previous calculations of 2$\pi$ production \cite{17}. However, in the partial decay width $D_{12} \to \pi d$, the cut-off parameter $\Lambda_{\pi d} = 0.3$ GeV was chosen in the present study, based on the abovementioned analogy with the $\Delta \to \pi N$ decay. On the other hand, an almost perfect description of the $2\pi$ production processes. \cite{37} was obtained with a different value $\Lambda_{\pi d} = 0.15$ GeV, found from the condition of the constant width near the resonance point (this is the simplest approximation for the decay width applicable in the vicinity of the resonance). As was shown above, the last choice of the parameter $\Lambda_{\pi d}$ leads to a slight disagreement with the empirical data for the one-pion production at low energies (see Fig. \ref{fig:9}), though considering the uncertainties in our calculation for background processes, this discrepancy can hardly be considered to be significant. On the contrary, one can suppose the $2\pi$-production cross sections to be more sensitive to the value of $\Lambda_{\pi d}$, when calculated on the basis of the resonance mechanism only, without account of background processes.

In the dibaryon model for $2\pi$ production \cite{37}, the amplitude for the reaction $pn \to d\pi^0\pi^0$ can be written as follows:

$$M_{\lambda_3,\lambda_3,\lambda_3} = \frac{\sum_{\lambda_3} M_{\lambda_3,\lambda_3,\lambda_3}}{s - M_{D_{12}}^2 + i\sqrt{s} \Gamma_{D_{12}}(s)}.$$  \hspace{1cm} (41)

When choosing the z axis to be parallel to the initial c.m. momentum $p$, the dibaryon $D_{03}$ formation amplitude takes the form

$$M_{\lambda_3,\lambda_3,\lambda_3} = \frac{\sum_{\lambda_3} M_{\lambda_3,\lambda_3,\lambda_3}}{s - M_{D_{03}}^2 + i\sqrt{s} \Gamma_{D_{03}}(s)}.$$  \hspace{1cm} (42)

$C^{\lambda_3}_{\lambda_3,\lambda_3,\lambda_3}$ being the Clebsch–Gordan coefficients. In its turn, for the dibaryon decay amplitudes, one gets the following expressions:

$$M_{\lambda_3,\lambda_3,\lambda_3} = \frac{\sum_{\lambda_3} M_{\lambda_3,\lambda_3,\lambda_3}}{s - M_{D_{03}}^2 + i\sqrt{s} \Gamma_{D_{03}}(s)}.$$  \hspace{1cm} (43)

where $\lambda_3$ is the solid spherical harmonics, expressed as functions of two momentum vectors, and $\mu = \lambda_3 - \lambda_3$.\footnote{For detailed derivation of Eqs. \ref{eq:42} \textit{-} \ref{eq:44} within the covariant $LS$-coupling scheme, see \cite{53}.}

The vertex functions are related to the partial decay widths as follows:

$$F_{R \to \alpha\beta}(p_{ab}) = M_{ab} \sqrt{\frac{8\pi\Gamma^{(l)}_{R \to \alpha\beta}(p_{ab})}{(p_{ab})^{2l+1}}}.$$  \hspace{1cm} (45)

Further, for the partial decay widths with meson emission, we chose the standard parametrization

$$\Gamma^{(l)}_{R \to \alpha\beta}(p) = \Gamma^{(l)}_{R \to \alpha\beta} \left( \frac{p}{p_0} \right)^{2l+1} \left( \frac{p_0 + \Lambda_{ab}}{p_0^2 + \Lambda_{ab}^2} \right)^{l+1},$$  \hspace{1cm} (46)

while for the $pn \to D_{03}$ vertex, we used the Gaussian form factor, according to the dibaryon model for $NN$ interaction \cite{44,47}. In this case, the $D_{03}$ decay width into np channel has the form similar to Eq. \ref{eq:41}. Parameters $\Lambda_{ab}$ were fixed by a condition of a constant width near the resonance point, so we found $\Lambda_{\pi d} = 0.18$, $\Lambda_{\pi N} = 0.09$, $\Lambda_{\pi D_{12}} = 0.12$ and $\Lambda_{\pi d} = 0.15$ GeV. For the latter parameter, we used also a higher value $\Lambda_{\pi d} = 0.3$ GeV which describes better the one-pion production process $p p \to d\pi^+\pi^-$ (see Sec. III).

The differential distribution on the invariant mass of two particles $b$ and $c$ can be found from the formula

$$\frac{d\sigma}{dM_{bc}} = \frac{1}{(4\pi)^3 p_s} \int \frac{d\Omega_{abc}}{d\Omega_{abc}} \frac{1}{\sqrt{M(p_s, p_{bc})^2}}.$$  \hspace{1cm} (47)

where $p_a$ is a c.m. 3-momentum of the particle $a$, $p_{bc}$ the particle $b$ and $c$ momentum in c.m.s. of two particles $b$ and $c$, and the line over the matrix element squared stands for averaging over the initial and summing over the final spin states. Then one gets for the total cross section:

$$\sigma = \int dM_{bc} \frac{d\sigma}{dM_{bc}}.$$  \hspace{1cm} (48)

The most sensitive quantity to the parameters of the $D_{12}$ dibaryon produced within a process $D_{03} \to D_{12} + \pi \to d + \pi$ \cite{37}, is the distribution on the invariant mass $M_{\pi \pi}$, while the total cross section as well as the $M_{\pi \pi}$ distribution are only slightly renormalized when changing the $D_{12}$ parameters. Fig. \ref{fig:9} shows the $M_{\pi \pi}$ distribution in the reaction $pn \to d\pi^0\pi^0$ at the peak energy $\sqrt{s} = 2.38$ GeV. Contrary to the supposition made at the beginning of this section, we found this distribution to be quite weakly dependent on the parameter $\Lambda_{\pi d}$. An increase of $\Lambda_{\pi d}$ from 0.15 to 0.3 GeV leads to only a small narrowing and increasing the peak by about 10%, thus worsening somewhat the agreement with experiment. However,
when using a slightly modified set of parameters for the dibaryon \( D_{12} \), i.e., \( M'_{D_{12}} = 2155 \) MeV, \( \Gamma'_{D_{12}} = 103 \) MeV and \( \Lambda'_{\sigma\pi} = 0.25 \) GeV (see set B in Table I), which gives an accurate description of the partial \( D_3 P \) cross section in the one-pion production process, we got an almost accurate description of the \( M_{d\pi} \) distribution in \( 2\pi \) production as well (cf. thin solid lines in Figs. 8 and 9), the main improvement being given again by a small increase in the \( D_{12} \) mass. This indicates the possibility of a very good simultaneous description of the independent empirical data for one- and two-pion production processes with the same realistic parameters of the \( D_{12} \) dibaryon.

On the other hand, we found that changing the \( D_{12} \) mass by 10–20 MeV does not lead to any shift of the resonance peak position in the \( M_{d\pi} \) spectrum in the \( 2\pi \) production process, in contrast to the cross section of the one-pion production reaction \( NN \to d\pi \). This reflects the fact that all final distributions in the reaction \( pn \to d(\pi\pi)0 \) must be symmetrized over two outgoing pions. As a consequence of this symmetry, simultaneous changes in two individual distributions for each pion largely cancel each other and are therefore weakly reflected in a final (observed) distribution. Given this fact, it is not surprising that the \( M_{d\pi} \) distribution is well reproduced also by a mechanism \( D_{03} \to \Delta\Delta \) \cite{30,31}, without the formal account of the \( D_{12} \) dibaryon. In this case, each individual-pion distribution on the \( d\pi \) invariant mass peaks near the \( N\Delta \) threshold located 20 MeV above the \( D_{12} \) mass. However, the final symmetrized \( M_{d\pi} \) distribution turns out to be almost the same as in case of intermediate \( D_{12} \) excitation. This makes difficult to disentangle the two \( D_{03} \) decay routes, i.e., \( D_{03} \to D_{12} + \pi \) and \( D_{03} \to \Delta\Delta \). From a general viewpoint, of course, one has to take both these routes into account. However, it is known from numerous six-quark microscopic calculations \cite{10,58,69} that the wave function of the \( \Delta\Delta \) system in the \( I(J^P) = 0(3^+) \) channel (corresponding to the \( D_{03} \) resonance) has a very small mean square radius \( r_{\Delta\Delta} \approx 0.7\)–0.9 fm, that is, two \( \Delta \) isobars in this state are almost completely overlapped with each other. Therefore it seems natural to assume that the main hadronic component of the \( D_{03} \) dibaryon, i.e., \( \Delta\Delta \), is not a physical system of two isolated \( \Delta \) isobars, which is highly unstable \( (\Gamma_{\Delta\Delta} \approx 2\Gamma_{\Delta} \approx 235 \) MeV), but only a specific 6\( \eta \)-configuration with quantum numbers of the \( \Delta\Delta \) system. It is also confirmed by an experimental observation that the \( D_{03} \) resonance width is much smaller than the total width of two isolated \( \Delta \) isobars: \( \Gamma_{D_{03}} \approx 70 \) MeV \( \ll \Gamma_{\Delta\Delta} \). In this context, the independent pion decay of two strongly overlapped \( \Delta \) isobars assumed in \cite{31,32} seems not fully justified from physical point of view. Therefore, it seems more natural to suggest that at least one of the final pions should be emitted from a dibaryon state, i.e., from the compact 6\( \eta \) object surrounded by meson fields, but not from an isolated \( \Delta \) isobar. One also needs to take into account that the width of the intermediate \( D_{12} + \pi \) state is about half the width of the \( \Delta + \Delta \) state, and thus the lifetime of the first is two times longer. So, the decay of the \( D_{03} \) resonance via the intermediate state \( D_{12} + \pi \) rather than \( \Delta + \Delta \) is likely to be regarded as the dominant one, although both above dibaryons can formally be described in terms of intermediate \( \Delta\Delta \) and \( N\Delta \) states \cite{32}.

The total cross section of the reaction \( pn \to d\pi^0\pi^0 \), going through the formation of the intermediate dibaryon \( D_{03}(2380) \) with a total width \( \Gamma_{D_{03}} = 70 \) MeV, is shown in Fig. 10. We obtained a very good agreement with experimental data at energies close to the resonance peak using the Gaussian form factor in the \( pn \to D_{03} \) vertex with a scale parameter \( \alpha(D_{03}) = 0.35 \) GeV which turned out to be larger than that for the \( pp \to D_{12} \) vertex \( \alpha(D_{12}) = 0.25 \) GeV. This result seems quite natural because the isoscalar resonance \( D_{03} \), according to quark-model estimates (see, e.g., \cite{18}), is characterized by a smaller radius than the isovector resonance \( D_{12} \).

On the other hand, Fig. 10 shows rather large discrepancies between our theoretical calculation and experimental data beyond the resonance peak. Particularly strong deviations are observed at energies \( \sqrt{s} \gtrsim 2.43 \) GeV. It is well known however \cite{31} that a significant contribution at these energies can be given by the conventional mechanism based on \( t \)-channel excitation of the intermediate \( \Delta\Delta \) system \cite{84}, being produced near its
threshold \((\sqrt{s})_{\Delta\Delta} = 2.46\) GeV. An additional enhancement of the cross section near the \(\Delta\Delta\) threshold can come from interference between the background \(t\)-channel process and the resonance \(D_{03}\) contribution which is though relatively small but still non-zero in this energy region (see Fig. 10).

![Diagram of cross section](image)

**Fig. 10:** (Color online) Total cross section of the reaction \(pn \rightarrow d\pi^0\pi^0\). The solid line shows the calculation in the dibaryon model which includes excitation of the isoscalar resonance \(D_{03}(2380)\) with the total width \(\Gamma_{D_{03}} = 70\) MeV. Filled circles correspond to the WASA@COSY experimental data \[31\] renormalized according to \[32\].

It is important to add here that the new measurements for the total cross section of the reaction \(pn \rightarrow pn\pi^0\pi^0\) at the energies \(T_p \approx 1\) GeV has been published recently by the WASA@COSY Collaboration \[30\]. The experiment clearly shows a significant strengthening of the cross section at \(T_p \approx 1.1\) GeV corresponding to excitation of the isoscalar resonance \(D_{03}(2380)\). Besides that, the dibaryon \(D_{03}\) excitation has been confirmed recently in the PWA of elastic \(np\) scattering \[31\], and the dibaryon parameters found there proved to be in good agreement with those derived from experimental data on 2\(\pi\) production.

The next important and nontrivial step towards establishing a connection between different hadronic processes and intermediate dibaryon resonances, is searching for isovector dibaryon signals in the processes of two-pion production in \(pp\) collisions.

### B. Isovector dibaryon signals in reactions \(pp \rightarrow d\pi\pi\) and \(pp \rightarrow pp\pi\pi\)

To the present authors’ knowledge, excitation of intermediate dibaryon resonances in two-pion production processes in isovector \(NN\) channels, like \(pp \rightarrow d\pi^+\pi^0\), \(pp \rightarrow pp\pi^0\pi^0\), etc., has not yet been considered in the literature. In fact, the mass of the basic isovector dibaryon \(D_{12}\) lies just at the 2\(\pi\)-production threshold \((\sqrt{s})_{NN\pi\pi} = (2m_p + 2m_\pi) \approx 2.15\) GeV, so its decay with two-pion emission is very unlikely. However the higher-lying isovector dibaryons found in \(pp\) elastic scattering in partial waves \(^3G_3, ^1G_4\), etc. \[3\], if they really exist, should decay into \(d\pi\pi\) and \(NN\pi\pi\) channels with a higher probability. Thus, the dibaryon \(D_{13}(2240)\) \((^3F_3)\) should be excited in \(pp\) collisions at energies \(T_p = (M_D^2/2m_p - 2m_\pi) \approx 800\) MeV, the dibaryon \(D_{14}(2430)\) \((^1G_4)\) — at \(T_p \approx 1.3\) GeV, etc. The possibility of finding the signals of these dibaryons in the 2\(\pi\)-production cross sections is determined mainly by the relative contributions of the resonance and background processes. However, as was already outlined above, one might expect the contributions of the background meson-exchange mechanisms (with relatively soft vertex cut-offs) to the two-pion production to be significantly less than to elastic scattering or one-pion production, since 2\(\pi\) production is generally accompanied by larger momentum transfers.

The conventional mechanisms of 2\(\pi\) production in \(pp\) collisions at energies \(T_p \approx 1\) GeV are based on \(t\)-channel excitation of the intermediate “pseudosonance” systems \(NR\) \((T_p \approx 0.9–1.1\) GeV\), where \(R\) is the Roper resonance \(N^*(1440)\), and \(\Delta\Delta\) \((T_p \approx 1.3–1.4\) GeV\). So, one may assume that the above meson-exchange mechanisms can interfere with the true resonance ones based on formation of intermediate isovector dibaryons. It should be borne in mind that the mass of the \(D_{14}(2430)\) dibaryon lies very close to the \(\Delta\Delta\)-excitation threshold \((\sqrt{s})_{\Delta\Delta} = 2.46\) GeV, so that the contribution of this dibaryon resonance may be difficult to separate from the contribution of the conventional \(t\)-channel \(\Delta\Delta\) process. One faces here in principle the same problems as in determining the relative contributions of the true resonance \(D_{12}(2150)\) and the “pseudosonance” \(N\Delta\) when studying the one-pion production processes. However, it should be emphasized once again that, due to short-range nature of the 2\(\pi\)-production processes, formation of a compact six-quark object (dibaryon) in this case can have a higher probability than the much more peripheral \(t\)-channel meson exchange, if the latter is calculated with the use of realistic (soft) vertex form factors. On the other hand, the mass of the resonance \(D_{13}(2240)\) lies 100–200 MeV below the excitation threshold of the \(NR\) system, so that the signal of this dibaryon at energies \(T_p \approx 800\) MeV can in principle be seen above the background, although the total cross sections of 2\(\pi\) production are very small in this energy region (2–3 \(\mu\)b only).

In order to get some preliminary insight, we compared experimentally measured total cross sections for the isoscalar reaction \(pn \rightarrow d\pi^0\pi^0\) \((\sigma_0)\) and the isovector one \(pp \rightarrow d\pi^+\pi^0\) \((\sigma_1)\) near the \(\Delta\Delta\) threshold. Thus, at the energy \(\sqrt{s} = 2.48\) GeV, where, according to the calculations \[85\], the conventional \(t\)-channel \(\Delta\Delta\) process gives the maximal contribution, one has \(\sigma_0 \approx 0.04\) mb
and $\sigma_1 \simeq 0.45$ mb (see Fig. 10 and Ref. 32). Even if to assume that the entire cross section of the reaction $pn \to d\pi^0\pi^0$ at this energy is given by the $t$-channel $\Delta\Delta$ mechanism, then the respective contribution of the same mechanism to the reaction $pp \to d\pi^+\pi^0$, according to the isospin relations [92], will be $\sigma_1(\Delta\Delta) = 5\sigma_0(\Delta\Delta) \simeq 0.2$ mb only. One can see that this value is two times less than the experimental one.\footnote{Supposedly, this fact has not been noticed before because the sufficiently accurate data on both above reactions were obtained only recently in works 41, 42, while the older data 71, 93 had lower statistics and hence rather large errors.}

This observation can be regarded as an indication of some additional isovector mechanism contribution in this energy region, and the $D_{13}(2430)$ resonance excitation seems to be very probable candidate here. In fact, the $t$-channel $\Delta\Delta$-excitation process is likely to give an even smaller contribution to both reactions in question, because the cross section in the isoscalar channel is not given entirely by the $t$-channel $\Delta\Delta$ process, but is partly resulted from the $D_{03}$ resonance excitation which is still non-zero near the $\Delta\Delta$ threshold (see Fig. 10).

We now turn to the reaction $pp \to ppp^0\pi^0$. The most intriguing feature of the total cross section of this reaction is a “shoulder” at energies $T_p = 1$–1.2 GeV (see Fig. 11), which is followed by a rather rapid increase as the energy approaches the $\Delta\Delta$ excitation threshold \footnote{Note that $t$-channel $\Delta\Delta$ process is even more sensitive to the cut-off parameter in the $\pi N\Delta$ vertex than the $N\Delta$ mechanism in one-pion production since the first process contains two such vertices.}.

The conventional model of the Valencia group \footnote{It is interesting to note that some attempts were made recently to modify the conventional Valencia model \footref{95} in order to describe the numerous new data \footref{94} on $2\pi$ production in $pp$ collisions. It was found \footref{94} that for re-} based on $t$-channel excitation of the intermediate states $NR + \Delta\Delta$, even with high cut-off parameters in vertices taken from the Bonn $NN$-potential model \footref{64},\footnote{In a more realistic calculation, of course, one has to take into account the interference of the dibaryon excitation mechanisms with the background processes. In particular, one can suggest that inclusion of interference between dibaryon $D_{13}(2430)$ production and the $t$-channel $\Delta\Delta$ excitation process will improve the data description. The most particular, one can suggest that inclusion of interference between dibaryon $D_{13}(2430)$ production and the $t$-channel $\Delta\Delta$ excitation process will improve the data description.} does not reproduce the observed behavior of experimental data because the theoretical cross section in this model increases uniformly with rising energy. However, the experimental data can in principle be explained by assuming the dominant contribution of the two known resonances: $D_{13}(2240)$ at $T_p \simeq 800$ MeV and $D_{14}(2430)$ at $T_p \simeq 1.3$ GeV. In this case, the total cross section of the reaction $pp \to ppp^0\pi^0$ can be described by the formula

$$\sigma = \sum_{J=3,4} \frac{\pi(2J + 1)}{p^2} \frac{2s \Gamma_{D_{13}}^{(i)}(s)}{(s - M_{D_{13}}^2)^2 + s \Gamma_{D_{13}}^2(s)} \frac{\Gamma_{D_{14}}^{(j)}(s)}{(s - M_{D_{14}}^2)^2 + s \Gamma_{D_{14}}^2(s)} \Gamma_{D_{14}\to pp}^2. \quad (49)$$

where $\Gamma_{D_{13}}^{(i)}(s)$ and $\Gamma_{D_{14}}^{(j)}(s)$ denote the partial widths of the resonance with a total angular momentum $J$ for the incoming ($pp$) and outgoing ($ppn^0\pi^0$) channels. As a first approximation, the total widths of the two resonances can be assumed constant and equal to $\Gamma_{D_{13}} = 150$ MeV. The incoming partial widths $\Gamma_{D_{14}\to pp}$ can also be considered constant in this energy range, but for comparison of the theoretical calculations with experimental data near the $2\pi$-production threshold one needs to take into account somehow the energy dependence of the outgoing widths $\Gamma_{D_{14}\to pppn^0\pi^0}$. In fact, they are proportional to the factor $(s - 4(m + n/2)^2)^n$, where the exponent $n$, in general, depends on the reaction dynamics. We found that the energy dependence of the total cross section for the reaction $pp \to ppp^0\pi^0$ in the near-threshold region can be reproduced well with $n = 4$. The results of calculations using Eq. (49), as well as the Valencia model \footref{95} predictions are shown in Fig. 11. Thus, to reproduce the experimental cross section in the vicinity of the incoming proton energies $T_p = 800$ MeV and 1.3 GeV, corresponding to the maximal excitation of the above two isovector resonances, their widths should satisfy the relations: $\Gamma_{D_{13}}^{(i)}(s)/\Gamma_{D_{14}}^{(j)}(s) \simeq 1.13 \times 10^{-6}$ and $5.63 \times 10^{-5}$ for the $D_{13}$ and $D_{14}$ dibaryons, respectively. If to suggest the incoming (elastic) partial widths of these dibaryons to be $\simeq 10\%$ of their total widths (as for the $D_{12}$ resonance) then we obtain the following estimates for the branching ratios of the $ppn^0\pi^0$ channel: $\Gamma_{D_{13}\to pppn^0\pi^0}/\Gamma_{D_{13}} \simeq 0.05\%$ and $\Gamma_{D_{14}\to pppn^0\pi^0}/\Gamma_{D_{14}} \simeq 2.5\%$. These estimates, as follows from Eq. (49), do not depend on neither the absolute values of the partial and total widths, nor the parametrization of their energy dependence. So, one can see that a very small fraction of the $ppn^0\pi^0$ channel in the isovector dibaryon decay widths is sufficient to describe the total cross section of the reaction $pp \to ppp^0\pi^0$ in terms of intermediate dibaryons only.

In a more realistic calculation, of course, one has to take into account the interference of the dibaryon excitation mechanisms with the background processes. In particular, one can suggest that inclusion of interference between dibaryon $D_{14}(2430)$ production and the $t$-channel $\Delta\Delta$ excitation process will improve the data description at $T_p \simeq 1.4$ GeV, and the $t$-channel excitation of the $NR$ system, due to the very large width of the Roper resonance, is likely to give a relatively smooth background at $T_p \simeq 1$ GeV. However, one can see already now that the dibaryon model, even in its simplest form presented here, describes the data on $2\pi$ production in $pp$ collisions in a rather broad energy range not worse than the conventional model based on $t$-channel excitation of hadronic resonances.

As was mentioned above, in the recent work \footref{94}, the total cross section of a similar reaction $pn \to pnn^0\pi^0$ in the GeV region has been measured. Experiment clearly shows an enhancement due to the isoscalar resonance $D_{03}(2380)$ production at energies $T_p \simeq 1.1$ GeV. Therefore, it seems quite natural that the isovector dibaryons $D_{13}^{(i)}(2240)$ and $D_{14}(2430)$ can be manifested in the reaction $pp \to ppp^0\pi^0$ at relevant energies (though the isovector resonance peaks will be smeared in comparison to a more pronounced isoscalar peak due to the larger widths of isovector resonances).
producing the basic features of the total and differential cross sections in the reaction \( pp \rightarrow pp\pi^0\pi^0 \), it is necessary to reduce the \( \rho \)-meson exchange in the original model \cite{3} by an order of magnitude (i.e., almost remove it). The meson-exchange vertex form factors were also dropped in this modified version of the model. In fact, such a modification corresponds to the account of the pion-exchange only, with the cut-off parameter \( \Lambda = \infty \). Although this model is hardly consistent with the actual physical picture, it describes the data very well \cite{45}. One could see here an interesting parallel with the above-cited work \cite{65}, where the deuteron properties were accurately described in a model including only pion exchange with \( \Lambda = \infty \), as well as with Ref. \cite{49}, where the total \( \pi^+d \rightarrow pp \) cross section in a broad energy range was shown to be described reasonably (though with incorrect normalization) within the same model. All these observations might probably be related to the general principle of continuity between hadron and quark d.o.f.

![Graph](image)

FIG. 11: (Color online) Total cross section of the reaction \( pp \rightarrow pp\pi^0\pi^0 \). The solid line shows the calculation in a model including the excitation of two intermediate dibaryon resonances \( D_{13}^-(2240) \) and \( D_{14}^+(2430) \). The individual contributions of the two resonance mechanisms are shown by short-dashed and dash-dotted lines, respectively. The long-dashed line corresponds to the Valencia model calculations \cite{25} with account of \( t \)-channel excitation of intermediate \( NR \) and \( \Delta\Delta \) states. The CELSIUS/WASA experimental data are shown by filled symbols and the older bubble-chamber data — by open symbols (see \cite{46} and references therein).

Thus, we have demonstrated that the one- and two-pion production processes in \( NN \) collisions can be consistently described in the model involving excitation of intermediate dibaryon resonances with realistic parameters. It has also been shown that the dibaryon parameters used do not contradict the empirical data on elastic \( NN \) and \( \pi d \) scattering.

To further clarify the relative role of the resonance and background contributions to the one- and two-pion production reactions in the GeV region, the more detailed knowledge of the basic dibaryon parameters, along with independent confirmation of the soft cut-off parameters in traditional meson-exchange mechanisms is required. However, as will be shown below, even at the present stage of our knowledge, an analysis of the inner structure and possible decay modes of intermediate dibaryons allow to give a qualitative explanation for some important experimental observations which find no obvious explanation within the conventional models.

V. TWO-PION PRODUCTION AND DIBARYON SPECTROSCOPY

In this section, we analyze the large differences between two-pion production cross sections in \( pn \) and \( pp \) collisions in the energy region \( T_p \sim 1 \) GeV in terms of intermediate dibaryon resonances and their spectra. In fact, the total cross section for production of the scalar-isoscalar pion pairs, i.e., \( \pi^0\pi^0 \) or \( (\pi^+\pi^-)_{\eta} \), in \( pp \) collisions at energies \( T_p = 1.1–1.2 \) GeV was found \cite{90,94} to be an order of magnitude higher than that in \( pp \) collisions. This difference was interpreted \cite{94} as a consequence of the isoscalar dibaryon \( D_{03}(2380) \) excitation which occurs in \( pn \) collisions only. It is important to emphasize that elastic cross sections for \( np \) and \( pp \) scattering are, on the contrary, very close to each other in the same energy region. Furthermore, the \( \pi\pi \) invariant mass distribution in the reaction \( pn \rightarrow d(\pi\pi)_{\eta} \) exhibits a pronounced near-threshold enhancement (the ABC effect) \cite{31,32}, whereas such an enhancement in the reaction with similar kinematics \( pp \rightarrow pp(1\,S_0)\pi^0\pi^0 \) turns out to be very modest, if present at all \cite{94}.

In our previous work \cite{37}, an abnormally high yield of the near-threshold scalar-isoscalar pion pairs observed in \( pn \) collisions was quantitatively interpreted as a result of constructive interference between two mechanisms of the \( D_{03}(2380) \) resonance decay: a direct decay to the final deuteron with emission of a light scalar \( \sigma \) meson (accompanied by a partial chiral symmetry restoration in a highly excited dibaryon state \cite{50}) and two consecutive one-pion decays via an intermediate isovector dibaryon \( D_{12}(2150) \) production. While the latter mechanism of sequential decay gives the rather uniform \( M_{\pi\pi} \) distribution, the mechanism of the \( \sigma \)-meson emission, though having a very small branching ratio, is highly concentrated near the two-pion threshold.

If we now suppose (see the previous section) that two-pion production in \( pp \) collisions in the GeV region occurs also to a large extent via intermediate (isovector) dibaryons formation, then it would be interesting to investigate the reasons for presence of the large ABC effect in \( pn \) and its almost absence in \( pp \) collisions from this point of view. For this purpose, it is important first to
establish the relationship between isoscalar and isovector dibaryons, as well as the impact of their possible quark structure on the probability of two-pion production.

A. Quark-cluster model for dibaryons

The parameters (masses and total widths) for experimentally found (non-strange) dibaryons and the theoretical predictions [11] based on SU(6) symmetry are summarized in Table II. Two theoretically predicted dibaryons which have not yet been found experimentally (see, however, [38]) are also presented in the table.

Regarding the possible quark structure of these dibaryons, one can follow theoretical arguments and the models developed by two groups, i.e., from Nijmegen [13] and ITEP [14], based partly on estimates for the masses of multiquark clusters obtained in the MIT-bag model. According to these models, the isovector dibaryons with $J^P = 2^+, 3^-, 4^+, 5^- , \ldots$ observed in $\bar{p} + p$ scattering as very inelastic resonances, have the two-cluster quark structure $[q^4 - q^2]$, i.e., consist of a tetraquark $q^4$ and a diquark $q^2$ connected by a colored QCD string. The tetraquark with a mass $M(q^4)$ = 1.05–1.15 GeV has the quantum numbers $S = 1, T = 0$, while the diquark here is an axial one, i.e., with quantum numbers $(S = T = 1)$ and a mass $M(q^2)$ = 450–550 MeV. In general, because the whole dibaryon states are colorless, while the quark clusters $q^4$ and $q^2$ as well as the string between them are colored objects, one is dealing in this case with a “hidden color” (first predicted by Brodsky et al. [96]; see also the recent paper [97]). So, the isovector and isoscalar dibaryons considered here can be classified as the typical hidden-color objects.

Next, according to [14], the observed series of isovector dibaryons lies on a relativistic Regge trajectory which describes rotational excitations of a relativistic string connecting two multiquark clusters. An important contribution to dibaryon masses is also given by the spin-orbit interaction between the quark clusters and the rotating string. In this case, the trajectory of isovector dibaryon states on the graph $[J, M \hbar^2]$ (where $J$ is a total dibaryon angular momentum) does not necessarily correspond to a straight line.

On the other hand, for relatively low energies of the rotational excitation $E^* = \Delta M \ll M_0$, where $M_0$ is a mass of the lowest rotational state, one can use the non-relativistic description of the rotational excitations in a clustered system $[q^4 - q^2]$ with an orbital angular momentum $L$ between the quark clusters. For successively increasing values of $L = 0, 1, 2, 3, \ldots$, one obtains the respective isovector dibaryons with alternating parities: $D_{12}(2.15), D_{13}(2.24), D_{14}(2.43), D_{15}(2.7), \ldots$. In this case, the rotational band of isovector dibaryons can be described by a simple non-relativistic formula (corresponding to the model of a rigid rotor) for the rotational states in the $[q^4 - q^2]$ system, with an additional term $M_{LS}$ due to the spin-orbit interaction:

$$M_D(L) = M_0 + \frac{\hbar^2}{2L} L(L + 1) + M_{LS},$$

where $L$ is a moment of inertia for the rotating quark-cluster system and the constant $\beta$ takes into account the kinetic energy of the rotating string itself.

Dependence of the isovector dibaryon masses $M_D$ on the quantity $L(L + 1)$ is shown in Fig. 12. It is clearly seen that the masses of the known isovector dibaryons are well fitted into a straight line. This gives a strong argument in favor of the above quark-cluster structure of dibaryons, with multiquark clusters at the ends of the rotating colored string, which is well described, at least for a few lowest states, by the non-relativistic rigid rotor model. In this case, the correction due to the spin-orbit interaction apparently does not lead to any significant deviation from a straight line on a graph $[L(L + 1), M_D]$.

It is interesting to note that in some previous works (see, e.g., [98]) the same isovector dibaryons were considered as lying on a rotational band in the $NN$ system, in the spirit of rotational bands in nuclear physics. It was found [98] that the trajectory of isovector dibaryons on the graph $[L_{NN}(L_{NN} + 1), M_D]$, where $L_{NN} = L + 2 = J$, is also rather close to a straight line. However, since the dibaryons are known to be highly inelastic in the $NN$ channel, the description in terms of quark clusters $[q^4 - q^2]$ rather than $[N - N]$ looks to be more appropriate.

In Fig. 12, the two known isoscalar dibaryons, i.e., the deuteron dibaryon $D_{01}(1.88)$ and the resonance $D_{13}(2.38)$, are also shown. These dibaryons are actually different from their isovector analogues with the same orbital angular momentum $L$, i.e., $D_{12}(2.15)$ and $D_{14}(2.43)$, respectively, by replacing the axial diquark by a scalar one, having quantum numbers $(S = T = 0)$. Accordingly, the spin-orbit interaction between the diquark and the colored string which shifts down the isovector dibaryon masses with $L > 0$ [14], should be turned off for their isoscalar partners. Then, assuming the isoscalar dibaryon series to be described by the above rigid rotor model, and drawing a straight line connecting the deuteron with the $D_{03}$ resonance, one can predict the existence of two isoscalar dibaryons of negative parity with masses lower than 3 GeV, namely, the $D_{02}(2.05)$ and $D_{04}(2.88)$. Since these dibaryons correspond to odd values of $L$ and thus $L + S + I = L + 1$ is an even number, they should be uncoupled from the $NN$ channel.

Actually, the dibaryon $D_{02}$ (or $d'$) corresponding to $L = 1$ was predicted previously by both the Nijmegen [13]

We omit the “+” superscript for the positive-parity states; dibaryon masses in GeV are shown in parentheses.
### TABLE II: Average parameters of dibaryon resonances found from experiments in comparison with theoretical predictions [11] given in the last column.

| D      | I(J^P) | 2S+1L_J(NN) | M^{exp} [GeV] | Γ_D [MeV] | M^{theo} [GeV] |
|--------|--------|-------------|--------------|-----------|--------------|
| D_{01} | 0(1^+) | 2S_1        | 1.88         | 0 (deuteron) | 1.88         |
| D_{03} | 0(3^+) | 3D_3        | ≃ 2.38       | ≃ 70       | 2.35         |
| D_{10} | 1(0^+) | 1S_0        | 1.88         | 0-0.5 (singlet deuteron) | 1.88 |
| D_{12} | 1(2^+) | 1D_2        | ≃ 2.15       | ≃ 120      | 2.16         |
| D_{13} | 1(3^-) | 3F_3        | ≃ 2.24       | ≃ 150      | —           |
| D_{14} | 1(4^+) | 1G_4        | ≃ 2.43       | ≃ 150      | —           |
| D_{15} | 1(5^-) | 3H_5        | ≃ 2.70       | ≃ 200      | —           |
| D_{21} | 2(1^+) | —           | —            | —          | 2.16         |
| D_{10} | 3(0^+) | —           | —            | —          | 2.35         |

According to the ITEP model [14], just the two-cluster structure with sufficiently separated multiquark clusters allows existence of the relatively long-lived 6q configurations with total widths Γ_{6q} ≃ 100–150 MeV, that is, of the same order as the Δ-isobar width. It is important to add here that the same effect of a 6q-system clustering into a tetraquark and a diquark was found also in S-wave NN interaction within the dibaryon model for nuclear force [46, 47]. Thus, clustering the dibaryons in the deuteron or singlet deuteron into a tetraquark q^4(S = 1, T = 0) or q^4(S = 0, T = 1), respectively, and a scalar diquark q^2(S' = T' = 0) is achieved by a two-quantum (2ℏω) excitation of a colored string with an orbital angular momentum L = 0. This 2ℏω excitation (being a simple consequence of the dominating s^2p^2 [42] symmetry in the 6q system [14]) gives rise to a node in the radial wave function of the multiquark system, which corresponds exactly to the two-cluster structure [q^4 − q^2], although in this case the quark clusters are in a relative S wave. It is important to note that the same picture for S-wave NN interaction was found also in a fully microscopic calculation of the 6q system in the resonating group method [100]. The authors [100] (see also [101]) found that the two-cluster configuration [q^4 − q^2] with a radial node in its relative-motion wave function dominates the six-quark wave function of the NN system in 3S_1 and 1S_0 channels. Thus, the clusterization of six-quark states seems to be a general phenomenon providing the relatively long-lived intermediate resonances in the NN interaction. So, it might play an essential role in the short-range nuclear force.

Given the above isovector and isoscalar rotational bands of dibaryons, one can consider the transitions between different dibaryon states via the meson emission. Thus, transitions between the eigenstates of two different bands can occur naturally via a pion emission changing a scalar diquark to an axial one and vice versa. Transitions within the same band can occur most likely via a string deexcitation through a light scalar (σ) meson emission. As was shown above, such transitions can generally be observed in one- or two-pion production processes in NN collisions however interfering with conventional processes involving intermediate baryonic resonances. The
most “clear” case in this respect seems the pure isoscalar reaction \( pn \rightarrow d(\pi\pi) \).

Now, using the above model for dibaryon resonances and also the results of Ref. [37], we consider the differences in the cross sections for two-pion production in \( pn \) and \( pp \) collisions at energies \( T_p \sim 1 \) GeV.

**B. Qualitative consideration of \( 2\pi \)-production in \( pn \) and \( pp \) collisions in terms of intermediate dibaryons**

Here, we focus mainly on presence of the pronounced near-threshold enhancement (ABC effect) in the \( M_{\pi\pi} \) spectrum in the isoscalar reaction \( pn \rightarrow d(\pi\pi) \) and the near absence of it in the similar isovector reaction \( pp \rightarrow pp(1S_0)(\pi\pi) \). First of all, it is important to emphasize that, even in the isoscalar \( NN \) channel, a significant ABC effect is observed only in case of the bound state (the deuteron) formation in the final \( pn \) system. This fact is confirmed by the latest measurements [90] for the reaction \( \sigma pn \rightarrow pn\pi^0\pi^0 \), which revealed a strong \( D_{03}(2380) \) resonance signal in the total cross section, but the very modest ABC enhancement in the \( M_{\pi\pi} \) spectrum. From the first sight, as claimed in [90], it may pose a problem for the interpretation of the ABC effect [37] as a consequence of a light scalar \( \sigma \) meson production within the process \( \sigma pn \rightarrow D_{03} \rightarrow d + \sigma \rightarrow d + (\pi\pi) \). However, a more detailed analysis reveals no real problems here. In fact, the \( M_{\pi\pi} \) distribution in reaction \( \sigma pn \rightarrow pn\pi^0\pi^0 \) is obtained by an integration over the available invariant masses \( M_{pn}^\prime \) of the final \( pn \) pair. Since the \( \sigma \)-meson is emitted in the \( D \) wave from the \( D_{03} \) decay, this process is concentrated near the \( M_{\pi\pi} \) threshold even in case of the final deuteron [37], the large centrifugal barrier will strongly suppress the \( \sigma \)-meson emission at higher \( M_{pn}^\prime \). Therefore, in the integrated \( M_{\pi\pi} \) distribution, the \( D_{03} \rightarrow pn + \sigma \) branch and thus the ABC enhancement should be hardly visible, in accordance with experimental data [90]. Besides that, the process \( D_{03} \rightarrow d + \sigma \) is likely to be dynamically selected from other final \( pn \) configurations, since it represents a direct transition between two discrete eigenstates of the \( 6q \) system. On the contrary, the process \( D_{03} \rightarrow D_{12} + \pi^0 \rightarrow pn\pi^0\pi^0 \) will “survive” the \( M_{pn}^\prime \) integration, since the decay of the resonance \( D_{12} \) into \( NN\pi \) channel is known to have a larger probability than that into \( d\pi \) channel. This may reflect the fact that the isovector resonance \( D_{12} \) have a large \( N + \Delta \) component, with the rather weakly bound \( N + \Delta \) system, unlike the deeply bound \( \Delta + \Delta \) system in the isoscalar \( D_{03} \) state. So, an intermediate \( N + \Delta \) state can give a large contribution to the \( D_{12} \) decay into \( NN\pi \) channel.

Let’s now turn to the \( 2\pi \) production reactions in the isovector \( NN \) channel. If one interprets \( 2\pi \) production in terms of intermediate dibaryons, then in case of \( pp \) collisions at energies \( T_p \sim 1 \) GeV, the two-pion emission should proceed most likely through the decay of intermediate isovector dibaryons\(^{13} \) \( F_3(2240) \) and \( G_4(2430) \) (see Sec. IV). It is easy to see however that the direct transitions \( D \rightarrow pp(1S_0) + \sigma \), where \( D \) is one of the above two dibaryons, with emission of a scalar \( \sigma \) meson, although possible in case of a low \( \sigma \) mass \( m_\sigma \sim 300 \) MeV (which may follow from chiral symmetry restoration in an excited dibaryon [37]), will be strongly suppressed by the centrifugal barrier, since the \( \sigma \) meson has to be emitted from the dibaryon \( ^3F_3 \) or \(^1G_4 \) decay in \( F \) or \( G \) waves, respectively. For comparison, in case of the isoscalar dibaryon \( D_{03}(2380) \) decay into \( d + \sigma \) channel, one has approximately the same available phase space as for the decay \( ^1G_4(2430) \rightarrow pp(1S_0) + \sigma \) (with the same mass of the \( \sigma \) meson), but the \( \sigma \) meson in first case is emitted in \( D \) wave, thus leading to a pronounced ABC enhancement in the \( 2\pi \) invariant-mass spectrum in the \( pn \rightarrow d(\pi\pi) \) reaction [37]. If we take into account the large width of the \(^1G_4(2430) \) dibaryon, then it is also possible to consider the decay \( ^1G_4(2430) \rightarrow D_{03}(2150) + \sigma \) with the \( D \)-wave \( \sigma \)-meson emission, but this decay route will be strongly suppressed due to the very small available phase space.

Furthermore, the decay of the above isovector dibaryons into the singlet deuteron \(^1S_0(1880) \) with emission of a scalar \( \sigma \) meson should be highly suppressed because of the quark structure of these dibaryon states. In the quark-cluster model for dibaryons described above, the dibaryon component of the singlet deuteron has the structure \( [q^4(S=0,T=1) - q^2(S'=T'=0)] \), whereas the structure of dibaryons \(^3F_3 \) and \(^1G_4 \) is \( [q^4(S=1,T=0) - q^2(S'=T'=1)] \). Therefore, in two-pion emission from such isovector dibaryons, the one-pion transition of an axial diquark into a scalar one, i.e., \( q^2(S'=T'=1) \rightarrow q^2(S'=T'=0) \), must be accompanied by a simultaneous one-pion Gamow-Teller transition in the tetraquark, i.e., \( q^4(S=1,T=0) \rightarrow q^4(S=0,T=1) \). Hence the generation of a tightly correlated scalar-isoscalar pion pair under such conditions should be very unlikely. On the contrary, the isoscalar dibaryon \( D_{03}(2380) \) and the dibaryon component of the deuteron have the same quark-cluster structure \( [q^4(S=1,T=0) - q^2(S'=T'=0)] \), thus the \( \sigma \) meson is emitted here via a direct deexcitation of the colored string from a rotational level \( L=2 \) to the ground level \( L=0 \), i.e., without rearrangement of the quark clusters themselves.

Thus, in general, emission of a light scalar \( \sigma \) meson near the \( 2\pi \) threshold which can explain the ABC effect in the isoscalar \( NN \) channel, appears to be very unlikely for the isovector channel. As a result, one comes to a conclusion well confirmed by experiments [94], that the ABC enhancement in reaction \( pp \rightarrow pp(\pi\pi) \), including the limiting case \( pp \rightarrow pp(1S_0)(\pi\pi) \), is very small, if visible at all (although it can still be manifested under

\(^{13}\) For the reader’s convenience, we denote here the isovector dibaryons by the respective quantum numbers of the \( NN \) channel.
certain kinematic conditions \[102\]).

Given the above arguments, it is possible to understand qualitatively the observed differences between two-pion production cross sections in \(pn\) and \(pp\) collisions. In this respect, the interpretation of \(2\pi\) production in \(NN\) collisions in terms of generation of intermediate dibaryon resonances and their possible decay modes with two-pion emission seems to be rather appropriate and natural.

VI. CONCLUSIONS

In this work, we analyzed the contributions of intermediate dibaryon resonances to the one- and two-pion production processes in \(NN\) collisions. Since these processes, in contrast to elastic scattering, are always accompanied by a large momentum transfer, i.e., involve the region of small inter-nucleon distances, a very important role in description of such processes is played by the short-range mechanisms of \(NN\) interaction, based on quark structure of interacting nucleons. In particular, in the overlap region of two nucleons, the probability of generation of the compact six-quark objects, i.e., dibaryon resonances, can increase considerably. This conclusion is confirmed in the present study by a comparative analysis of contributions of \(s\)-channel dibaryon-formation and \(t\)-channel meson-exchange mechanisms to the elastic \(pp\) and \(\pi^+d\) scattering and the one-pion production reaction \(pp \rightarrow d\pi^+\). An even more pronounced manifestation of intermediate dibaryon resonances is expected in two-pion production reactions. In addition to the continuing study of the isoscalar \(0(3^+)\) resonance observed recently in two-pion production in \(pn\) collisions \[31\], we proposed searching the signals of isovector dibaryons in \(pp\) collisions.

However, as shown by numerous studies including the present work, the contributions of short-range QCD mechanisms can often be simulated rather accurately by the conventional meson-exchange mechanisms (with appropriate parameter fitting). This fact can explain the success of meson-exchange models in the description of many hadronic and electromagnetic processes including those with high momentum transfers. However, while the long-range part of \(NN\) interaction is described universally by \(t\)-channel meson-exchange mechanisms (mainly by one- and two-pion exchange) and poses no doubts, an effective description of its short-range part requires introducing the specific mechanisms and careful adjusting their parameters (mainly the vertex cut-offs) \textit{ad hoc} to a particular process. These parameters entering the same mechanisms should be changed to describe the different processes and are often not consistent with microscopic predictions. As an example, one can consider the large differences between the short-range cut-off parameter in the \(\pi N\Delta\) vertex, needed to describe elastic \(\pi N\) scattering, from parameters in the same vertex used in realistic potential models for \(NN\) interaction, in conventional models for one-pion production and others. In other words, the description of short-range processes in traditional meson-exchange models is not entirely consistent and contains a number of inner contradictions (see discussion on this issue in \[66\]).

On the other hand, in effective description of the short-range QCD mechanisms of \(NN\) interaction by using dibaryon degrees of freedom, the dibaryon parameters used in calculations of various hadronic and nuclear processes are in a good agreement with each other. It is important to realize that QCD-motivated dibaryon mechanisms at small inter-nucleon distances do not contradict the traditional meson-exchange picture at the large and intermediate distances, but rather complement it. The dibaryon generation does not actually contradict also the heavy-meson exchange, provided the realistic (soft) cut-off parameters in the respective vertices are used. However, concerning generation of the heavy vector mesons \(\rho\) and \(\omega\) at short \(NN\) distances, it seems more natural to assume these mesons emerging from a unified meson cloud of a six-quark object (dibaryon) than in \(t\)-channel exchange between two isolated nucleons at distances \(r_{NN} \sim 0.2\) fm, where the quark cores of two nucleons are strongly overlapped (see the detailed discussion in \[103\]).

Thus, we believe that dibaryons are much more intriguing objects than just multiquark exotics, which might be manifested under specific experimental conditions. They seem to be a manifestation of the fundamental properties of nonperturbative QCD, which drive the \(NN\) interaction at short distances and, in general, the short-range correlations in nuclei. The quantitative verification of this hypothesis requires further theoretical and experimental research.

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