An Isotensor Dibaryon in the $pp \to pp\pi^+\pi^-$ Reaction?

P. Adlarson,[1] W. Augustyniak,[2] W. Bardan,[3] M. Bashkanov,[4] F.S. Bergmann,[5] M. Berłowski,[6] A. Bondar,[7,8] M. Büscher,[9,10] H. Calén,[1] I. Ciepał,[11] H. Clement,[12,13] E. Czerwiński,[3] K. Demmich,[5] R. Engels,[14] A. Erven,[15] W. Erven,[15] W. Eyrich,[16] P. Fedorets,[14,17] K. Föhl,[18] K. Fransson,[1] F. Goldenbaum,[14] A. Goswami,[14,19] K. Grigoryev,[14,20] L. Heijkenskjöld,[1,*] V. Hejny,[14] N. Hüsken,[5] L. Jarczyk,[3] T. Johansson,[1] B. Kamys,[3] G. Kemmerling,[15,†] A. Khoukaz,[5] O. Khreptak,[3] D.A. Kirillov,[21] S. Kistryn,[3] H. Kleines,[15,†] B. Kłos,[22] W. Krzemień,[6] P. Kulessa,[11] A. Kupść,[1,6] K. Lalwani,[23] D. Lersch,[14,‡] B. Lorentz,[14] A. Magiera,[3] R. Maier,[14,24] P. Marciniewski,[1] B. Mariański,[2] H.–P. Morsch,[2] P. Moskal,[3] H. Ohm,[14] W. Parol,[11] E. Perez del Rio,[12,13,§] N.M. Piskunov,[21] D. Prasuhn,[14] D. Pszczel,[1,6] K. Pysz,[11] J. Ritman,[14,24,25] A. Roy,[19] Z. Rudy,[3] O. Rundel,[3] S. Sawant,[26] S. Schadmand,[14] I. Schätti–Ozerianska,[3] T. Sefzick,[14] V. Serdyuk,[14] B. Shwartz,[7,8] T. Skorodko,[12,13,27] M. Skurzok,[3] J. Smyrski,[3] V. Sopov,[17] R. Stassen,[14] J. Stepaniak,[6] E. Stephan,[22] G. Sterzenbach,[14] H. Stockhorst,[14] H. Ströher,[14,24] A. Szczurek,[11] A. Trzciński,[2] M. Wolke,[1] A. Wrońska,[3] P. Wüstner,[15] A. Yamamoto,[28] J. Zabierowski,[29] M.J. Zieliński,[3] J. Złomańczuk,[1] P. Żupráński,[2] and M. Żurek[14]
(WASA-at-COSY Collaboration)

[1] *Division of Nuclear Physics, Department of Physics and Astronomy, Uppsala University, Box 516, 75120 Uppsala, Sweden*
[2] *Nuclear Physics Division, National Centre for Nuclear Research, ul. Hoza 69, 00-681, Warsaw, Poland*
[3] *Institute of Physics, Jagiellonian University, prof. Stanisława Łojasiewicza 11, 30-348 Kraków, Poland*
[4] *School of Physics and Astronomy, The University of Edinburgh, James Clerk Maxwell Building, Peter Guthrie Tait Road, Edinburgh EH9 3FD, Great Britain*
[5] *Institut für Kernphysik, Westfälische Wilhelms–Universität Münster, Wilhelm–Klemm–Str. 9, 48149 Münster, Germany*
[6] *High Energy Physics Division, National Centre for Nuclear Research, ul. Hoza 69, 00-681, Warsaw, Poland*
[7] *Budker Institute of Nuclear Physics of SB RAS, 11 Acad. Lavrentieva Pr., Novosibirsk, 630090 Russia*
[8] *Novosibirsk State University, 2 Pirogova Str., Novosibirsk, 630090 Russia*
[9] *Peter Grünberg Institut, PGI–6 Elektronische Eigenschaften, Forschungszentrum Jülich, 52425 Jülich, Germany*
[10] *Institut für Laser– und Plasmaphysik, Heinrich Heine Universität Düsseldorf, Universitätsstr. 1, 40225 Düsseldorf, Germany*
[11] *The Henryk Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego 152, 31-342 Kraków, Poland*
[12] *Physikalisches Institut, Eberhard Karls Universität Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany*
[13] *Kepler Center for Astro and Particle Physics, Physikalisches Institut der Universität Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany*
[14] *Institut für Kernphysik, Forschungszentrum Jülich, 52425 Jülich, Germany*
[15] *Zentralinstitut für Engineering, Elektronik und Analytik, Forschungszentrum Jülich, 52425 Jülich, Germany*
[16] *Physikalisches Institut, Friedrich–Alexander Universität Erlangen–Nürnberg, Erwin–Rommel-Str. 1, 91058 Erlangen, Germany*
[17] *Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of National Research Centre "Kurchatov Institute", 25 Bolshaya Cheremushkinskaya Str., Moscow, 117218 Russia*
[18] *II. Physikalisches Institut, Justus–Liebig–Universität Gießen, Heinrich–Buff–Ring 16, 35392 Giessen, Germany*
[19] *Discipline of Physics, Indian Institute of Technology Indore, Khandwa Road, Indore, Madhya Pradesh 453 552, India*
[20] *High Energy Physics Division, Petersburg Nuclear Physics Institute named by B.P. Konstantinov of National Research Centre "Kurchatov Institute", 1 mkr. Orlova roshcha, Leningradskaya Oblast, Gatchina, 188300 Russia*
[21] *Veksler and Baldin Laboratory of High Energiy Physics, Joint Institute for Nuclear Physics, 6 Joliot–Curie, Dubna, 141980 Russia*
[22] *August Chełkowski Institute of Physics, University of Silesia, ul. 75 Pułku Piechoty 1, 41-500 Chorzów, Poland*
[23] *Department of Physics, Malaviya National Institute of Technology Jaipur, JLN Marg, Jaipur, Rajasthan 302 017, India*
[24] *JARA–FAME, Jülich Aachen Research Alliance, Forschungszentrum Jülich, 52425 Jülich, and RWTH Aachen, 52056 Aachen, Germany*
[25] *Institut für Experimentalphysik I, Ruhr–Universität Bochum, Universitätsstr. 150, 44780 Bochum, Germany*
[26] *Department of Physics, Indian Institute of Technology Bombay, Powai, Mumbai, Maharashtra 400 076, India*
[27] *Department of Physics, Tomsk State University, 36 Lenin Ave., Tomsk, 634050 Russia*
[28] *High Energy Accelerator Research Organisation KEK, Tsukuba, Ibaraki 305–0801, Japan*
[29] *Astrophysics Division, National Centre for Nuclear Research, Box 447, 90-950 Łódź, Poland*

(Dated: April 19, 2018)

Exclusive measurements of the quasi-free $pp \to pp\pi^+\pi^-$ reaction have been carried out at WASA@COSY by means of pd collisions at $T_p = 1.2$ GeV. Total and differential cross sections have been extracted covering the energy region $T_p = 1.08 - 1.36$ GeV, which is the region of $N^*(1440)$ and $\Delta(1232)\Delta(1232)$ resonance excitations. Calculations describing these excitations by t-channel meson exchange are at variance with the measured differential cross sections and underpredict substantially the experimental total cross section. An isotensor ΔN dibaryon resonance with $I(J^P) = 2(1^+)$ produced associatedly with a pion is able to overcome these deficiencies.

PACS numbers: 13.75.Cs, 14.20.Gk, 14.20.Pt
Keywords: Two-Pion Production, $\Delta\Delta$ Excitation, Roper Resonance, Dibaryon Resonance

I. INTRODUCTION

In recent years the two-pion production in nucleon-nucleon (NN) collisions has been measured from threshold up to incident energies of $T_p = 1.4$ GeV by exclusive and kinematically complete high-statistics experiments at CELSIUS [1–9] and COSY [10–17]. Within these systematic studies the first clear-cut evidence for a dibaryon resonance with $I(J^P) = 0(3^+)$ was observed in the $pn \to d\pi^0\pi^0$ reaction [9, 13, 14]. Subsequent measurements of the $pn \to d\pi^+\pi^-$ [15], $pn \to pp\pi^0\pi^-$ [16], $np \to np\pi^0\pi^0$ [17] and $pn \to pn\pi^+\pi^-$ [18–20] reactions revealed that all these reaction channels, which contain isoscalar contributions, exhibit a signal of this resonance — called now $d^*(2380)$ after observation of its pole in pn scattering [21–23]. It corresponds to $D_{IJ} = D_{03}$ predicted by Dyson and Xuong [24] as one of six non-strange dibaryon states. Other members of the dibaryon multiplet are the deuteron groundstate (D_{01}), the virtual $^1S_0$ state (D_{10}) as well as the ΔN threshold states D_{12} and D_{21} — with the latter one being still purely hypothetical.

According to the standard theoretical description, the two-pion production process at the energies of interest here is dominated by t-channel meson exchange leading to excitation and decay of the Roper resonance $N^*(1440)$ and of the $\Delta(1232)\Delta(1232)$ system [25, 26]. Whereas in the near-threshold region the Roper process dominates, the $\Delta\Delta$ process takes over at incident energies beyond 1 GeV. Such calculations give quite a reasonable description of the data, if for the Roper resonance the up-to-date decay branchings [27, 28] are used and if the ρ exchange contribution of the $\Delta\Delta$ process is tuned to describe quantitatively the $pp \to pp\pi^0\pi^0$ data ("modified Valencia" calculations) [7] — and if in the pn-induced channels the $d^*(2380)$ resonance is taken into account.

However, in reexamining the pp-induced two-pion production channels we find that for the $pp \to pp\pi^+\pi^-$ reaction beyond 0.9 GeV the calculated cross sections come out now much too low (see dashed line in Fig. 1). This problem was already noted in the isospin decomposition of pp-induced two-pion production [5]. The discrepancy in the $pp\pi^+\pi^-$ cross section appears just in the region, where the isotensor dibaryon state D_{21} with $I(J^P) = 2(1^+)$ was predicted by Dyson and Xuong [24] and more recently also calculated by Gal and Garcilazo [29].

Since all $pp \to pp\pi^+\pi^-$ data beyond 0.8 GeV stem from early low-statistics bubble-chamber measurements [30–36], it appeared appropriate to reinvestigate this region by exclusive and kinematically complete measurements.

II. EXPERIMENT

The $pp \to pp\pi^+\pi^-$ reaction was measured by use of the quasifree process in pd collisions. The experiment was carried out at COSY (Forschungszentrum Jülich) with the WASA detector setup by using a proton beam of lab energy $T_p = 1.2$ GeV impinging on a deuterium pellet target [37, 38]. By exploiting the quasi-free scattering process $pd \to pp\pi^+\pi^- + n_{spectator}$, we cover the energy region $T_p = 1.08 - 1.36$ GeV corresponding to $\sqrt{s} = 2.35$ - 2.46 GeV.

The hardware trigger utilized in this analysis required two charged hits in the forward detector as well as two recorded hits in the central detector.

The quasi-free reaction $pd \to pp\pi^+\pi^- + n_{spectator}$ was selected in the offline analysis by requiring two proton tracks in the forward detector as well as a π^+ and π^- track in the central detector.

That way, the non-measured spectator four-momentum could be reconstructed by a kinematic fit with one over-constraint. The achieved resolution in $\sqrt{s}$ was about 20 MeV.

The charged particles registered in the segmented forward detector of WASA have been identified by use of the $\Delta E - E$ energy loss method. For its application in the data analysis, all combinations of signals stemming from the five layers of the forward range hodoscope have been used. The charged particles in the central detector have been identified by their curved track in the magnetic field as well as by their energy loss in the surrounding plastic scintillator barrel and electromagnetic calorimeter.

The requirement that the two protons have to be in the angular range covered by the forward detector and that two pions have to be within the angular range of the central detector reduces the overall acceptance to about 30%. The total reconstruction efficiency including all cuts and kinematical fit has been 1.1%. In total a sample of about 26000 $pp\pi^+\pi^-$ events has been selected, which satisfy all cuts and conditions.

Efficiency and acceptance corrections of the data have been performed by MC simulations of reaction process and detector setup. For the MC simulations pure phase-space and model descriptions have been used. The latter will be discussed in the next section. Since WASA does not cover the full reaction phase space, albeit a large fraction of it, these corrections are not fully model independent. The hatched grey histograms in Figs. 2 - 3 give an

* present address: Institut für Kernphysik, Johannes Gutenberg Universität Mainz, Johann–Joachim–Becher Weg 45, 55128 Mainz, Germany
† present address: Jülich Centre for Neutron Science JCNS, Forschungszentrum Jülich, 52425 Jülich, Germany
‡ present address: Department of Physics, Florida State University, 77 Chieftan Way, Tallahassee, FL 32306-4350, USA
§ present address: INFN, Laboratori Nazionali di Frascati, Via E. Fermi, 40, 00044 Frascati (Roma), Italy

estimate for these systematic uncertainties. As a measure of these we take the difference between model corrected results and those obtained by assuming the "modified Valencia" calculations for the acceptance

The absolute normalization of the data has been obtained by comparison of the simultaneously measured quasi-free single pion production process $pd \to pp\pi^0 + n_{spectator}$ to previous bubble-chamber results for the $pp \to pp\pi^0$ reaction [32, 34]. That way, the uncertainty in the absolute normalization of our data is essentially that of the previous $pp \to pp\pi^0$ data, *i.e.* in the order of 5 - 15%. Details of the data analysis and of the interpretation are given in Ref. [39].

III. RESULTS AND DISCUSSION

In order to determine the energy dependence of total and differential cross sections for the quasi-free process, we have divided our background corrected data into bins of 50 MeV width in the incident energy T_p. The resulting total cross sections are shown in Fig. 1 (solid circles) together with results from earlier measurements (open symbols) [1–3, 12, 31–34, 36]. Our data for the total cross section are in reasonable agreement with the earlier measurements.

In order to compare with theoretical expectations we plot in Fig. 1 the results of the "modified Valencia" calculations by the dashed line. These calculations do very well at low energies, but underpredict substantially the data at higher energies. The reason is that by isospin relations $pp\pi^0\pi^0$ and $pp\pi^+\pi^-$ channels have to behave qualitatively similar, if only t-channel Roper and $\Delta\Delta$ processes contribute. So, if the kink around $T_p \approx 1.1$ GeV in the $pp\pi^0\pi^0$ data [7] got to be reproduced by any such model calculation, then also the $pp\pi^+\pi^-$ channel has to behave such, if not a new strong and very selective ρ channel $\pi^+\pi^-$ production process enters [39].

Next we consider the differential cross sections. For a four-body, axially symmetric final state there are seven independent differential observables. For a better discussion of the physics issue we choose to show in this paper nine differential distributions, namely those for the center-of-mass (c.m.) angles for protons and pions denoted by $\Theta_p^{c.m.}$, $\Theta_{\pi^+}^{c.m.}$ and $\Theta_{\pi^-}^{c.m.}$, respectively, as well as those for the invariant masses M_{pp}, $M_{\pi^+\pi^-}$, $M_{p\pi^+}$, $M_{pp\pi^+}$, $M_{p\pi^-}$ and $M_{pp\pi^-}$. These distributions are shown in Figs. 2 - 3.

There are no data to compare with from previous experiments in the energy range considered here. All measured differential distributions are markedly different from pure phase-space distributions (shaded areas in Figs. 2 - 3). With the exception of $\Theta_{\pi^+}^{c.m.}$, $M_{p\pi^-}$ and $M_{pp\pi^-}$ spectra, the differential distributions are reasonably well reproduced by the "modified Valencia model" calculations (dashed curves). For better comparison all calculations are adjusted in area to the data in Figs. 2 - 3.

The proton angular distribution is strongly forward-

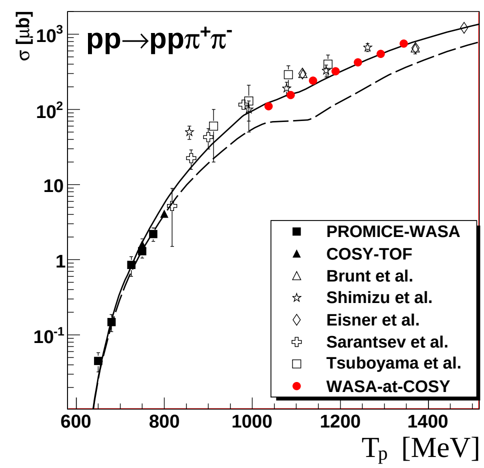

FIG. 1. (Color online) Total cross section in dependence of the incident proton energy T_p for the reaction $pp \to pp\pi^+\pi^-$. The solid dots show results from this work. Other symbols denote results from previous measurements [1–3, 12, 31–34, 36]. The dashed line gives the "modified Valencia" calculation [7]. The solid line is obtained, if an associatedly produced D_{21} resonance is added according to the process $pp \to D_{21}\pi^- \to pp\pi^+\pi^-$ with a strength fitted to the total cross section data.

backward peaked as expected for a peripheral reaction process. The π^- angular distribution is rather flat, in tendency slightly convex curved, as also observed in the other $NN\pi\pi$ channels in this energy range.

But surprisingly, the π^+ angular distribution exhibits an opposite curvature, a strikingly concave shape. Such a behavior, which is in sharp contrast to the theoretical expectations, has been observed so far in none of the two-pion production channels [39].

Also the $M_{p\pi^-}$ and $M_{pp\pi^-}$ spectra are markedly different from the $M_{p\pi^+}$ and $M_{pp\pi^+}$ spectra, respectively. In case of the t-channel $\Delta\Delta$ process, which is usually considered to be the dominating one at the energies of interest here, Δ^{++} and Δ^0 get excited simultaneously and with equal strength. Hence, the $M_{p\pi^-}$ ($M_{pp\pi^-}$) spectrum should be equal to the $M_{p\pi^+}$ ($M_{pp\pi^+}$) one and the π^+ angular distribution should equal the π^- angular distribution.

So this observation plus the failure of the "modified Valencia" calculation to describe properly both the total cross section and the differential distributions suggest that the t-channel $\Delta\Delta$ process is not the leading one here.

It looks that an important piece of reaction dynamics is missing, which selectively affects the π^+, $p\pi^-$ and $pp\pi^-$ subsystems in the $pp\pi^+\pi^-$ channel. Further-on, since the discrepancy between data and "modified Valencia" description opens up scissor-like around $T_p \approx 0.9$ GeV, it would match the opening of a new channel, where a ΔN system is produced associatedly with another pion. Such a state with the desired properties could be the isotensor D_{21} state with $I(J^P) = 2(1^+)$ predicted already

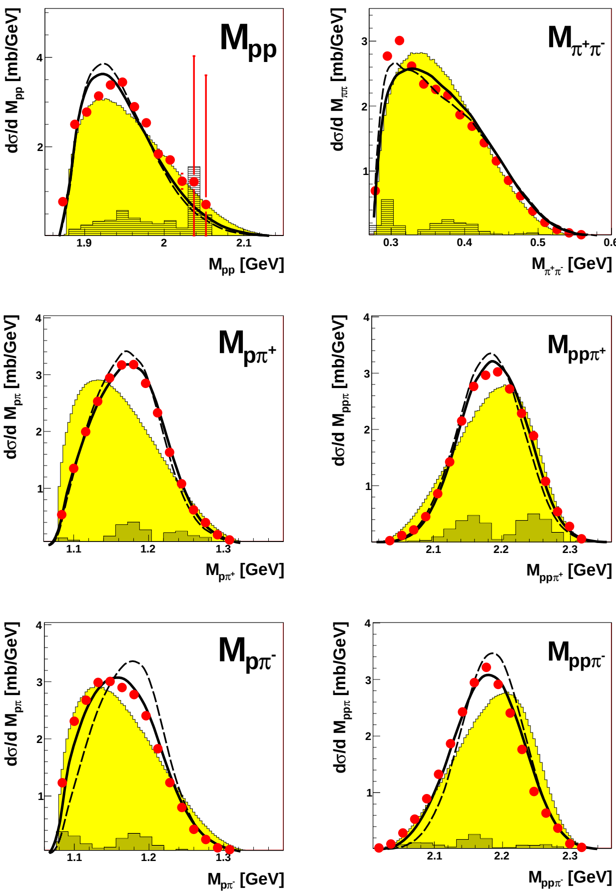

FIG. 2. (Color online) Differential distributions of the $pp \to pp\pi^+\pi^-$ reaction in the region T_p = 0.9 - 1.3 GeV for the invariant-masses M_{pp} (top left), $M_{\pi^+\pi^-}$ (top right), $M_{p\pi^+}$ (middle left), $M_{pp\pi^+}$ (middle right), $M_{p\pi^-}$ (bottom left), $M_{pp\pi^-}$ (bottom right). Filled circles denote the results from this work. The hatched histograms indicate systematic uncertainties due to the restricted phase-space coverage of the data. The shaded areas represent pure phase-space distributions, dashed lines "modified Valencia" calculations [25] ([7]). The solid lines include the process $pp \to D_{21}\pi^- \to pp\pi^+\pi^-$. All calculations are normalized in area to the data.

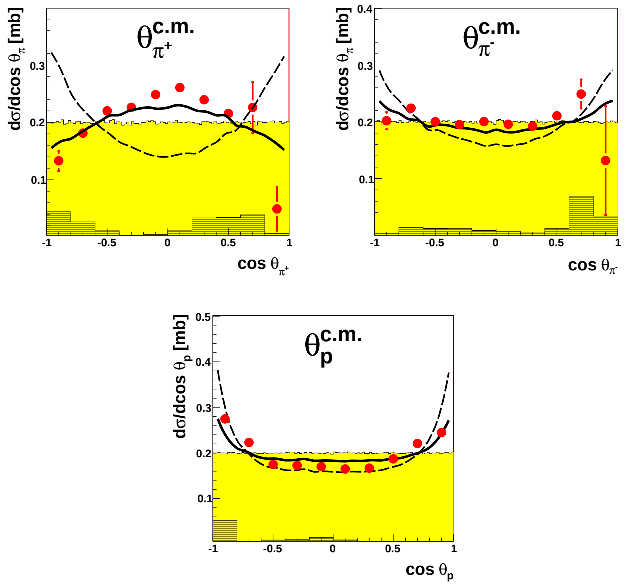

FIG. 3. (Color online) The same as Fig. 2, but for the c.m. angles of positive and negative pions $\Theta_{\pi^+}^{c.m.}$ and $\Theta_{\pi^-}^{c.m.}$, respectively, as well as protons $\Theta_p^{c.m.}$.

by Dyson and Xoung [24] with a mass in the region of its isospin partner D_{12} with $I(J^P) = 1(2^+)$. The latter has been observed with a mass of about 2144 - 2148 MeV [40, 41], *i.e.* with a binding energy of a few MeV relative to the nominal ΔN threshold and with a width compatible to that of the Δ. For a recent discussion about the nature of this D_{12} state see, *e.g.*, Ref. [42].

Due to its isospin $I = 2$ D_{21} cannot be reached directly by the initial pp collisions, but only be produced associatedly with an additional pion. The hypothetical isotensor state D_{21} strongly favors the purely isotensor channel $pp\pi^+$ in its decay. In addition, $J^P = 1^+$ can be easily reached by adding a p-wave pion (from Δ decay) to a pp pair in the $^1S_0$ partial wave. Hence – as already suggested by Dyson and Xuong [24] – the favored production process should be $pp \to D_{21}\pi^- \to pp\pi^+\pi^-$.

Quantitatively the process can be described by using the formalism outlined in Refs. [39, 43]. The D_{21} resonance can be formed together with an associatedly produced pion either in relative s or p wave. In the first instance the initial pp partial wave is $^3P_1$, in the latter one it is $^1S_0$ or $^1D_2$. The first case is special, since only this one yields a $sin\Theta_\pi$ dependence for the angular distribution of the pion originating from the D_{21} decay — exactly what is needed for the description of the data for the π^+ angular distribution.

In fact, if we add such a resonance assuming the process $pp \to D_{21}\pi^- \to pp\pi^+\pi^-$ with fitted mass $m_{D_{21}}$ = 2140 MeV and width $\Gamma_{D_{21}}$ = 110 MeV, we obtain a good description of the total cross section by adjusting the strength of the assumed resonance process to the total cross section data (solid line in Fig. 1). Simultaneously, the addition of this resonance process provides a quantitative description of all differential distributions (solid lines in Figs. 2 - 3), in particular also of the $\Theta_{\pi^+}^{c.m.}$, $M_{p\pi^-}$ and $M_{pp\pi^-}$ distributions. Since the D_{21} decay populates only Δ^{++}, its reflexion in the $M_{p\pi^-}$ spectrum shifts the strength to lower masses – as required by the data. The same holds for the $M_{pp\pi^-}$ spectrum. We are not aware of any other mechanism, which could provide an equally successful description of the observables of the $pp \to pp\pi^+\pi^-$ reaction at the energies of interest here.

We note that the only other place in pion production, where a concave curved pion angular distribution has been observed, is the $pp \to pp\pi^0$ reaction in the region of single Δ excitation [44, 45]. Also in this case it turned out that the reason for it was the excitation of resonances in the ΔN system [45].

Though the addition of an isotensor dibaryon resonance cures the shortcomings of the "modified Valencia" calculations for the $pp \to pp\pi^+\pi^-$ reaction, we have to investigate, whether such an addition leads to inconsistencies in the description of other two-pion production channels, since such a state may decay also into $NN\pi$ channels other than $pp\pi^+$ — though with a much smaller branchings due to isospin coupling. In consequence it may also contribute to other two-pion production channels. This is particularly relevant for the $pp \to pp\pi^0\pi^0$ reaction with its comparatively small cross section at the energies of interest here. But the D_{21} production via the $^3P_1$ partial wave leaves the two pions in relative p-wave, hence they are also in an isovector state by Bose symmetry. Since such a ρ-channel situation is not possible for identical pions, there are no contributions from D_{21} in $pp\pi^0\pi^0$ and $nn\pi^+\pi^+$ channels, *i.e.* there is no consistency problem.

From a fit to the data we obtain a mass $m_{D_{21}} = 2140(10)$ MeV and a width $\Gamma_{D_{21}} = 110(10)$ MeV. The mass is in good agreement with the prediction of Dyson and Xuong [24]. Both mass and width are just slightly smaller than those calculated by Gal and Garcilazo [29].

IV. SUMMARY AND CONCLUSIONS

Total and differential cross sections of the $pp \to pp\pi^+\pi^-$ reaction have been measured exclusively and kinematically complete in the energy range $T_p = 1.08 - 1.36$ GeV ($\sqrt{s} = 2.35$ - 2.46 GeV) by use of the quasi-free process $pd \to pp\pi^+\pi^- + n_{spectator}$. The results for the total cross section are in good agreement with previous bubble-chamber data. For the differential cross sections no data from previous measurements are available.

The $M_{p\pi^-}$, $M_{pp\pi^-}$ and $\Theta_{\pi^-}^{c.m.}$ distributions are observed to be strikingly different from their counterparts, the $M_{p\pi^+}$, $M_{pp\pi^+}$ and $\Theta_{\pi^+}^{c.m.}$ distributions, respectively. Hence the originally anticipated t-channel $\Delta\Delta$ mechanism cannot be the dominating process here.

The problem can be overcome, if there is an opening of a new reaction channel near $T_p \approx 0.9$ GeV, *i.e.*, near the $\Delta N\pi$ threshold, which nearly exclusively feeds the $pp\pi^+\pi^-$ channel. Such a process is the associated production of the theoretically predicted isotensor ΔN state D_{21} with specific signatures in invariant mass spectra and in the π^+ angular distribution. We have demonstrated that such a process provides a quantitative description of the data for the $pp \to pp\pi^+\pi^-$ reaction — both for the total cross section and for all differential distributions.

V. ACKNOWLEDGMENTS

We acknowledge valuable discussions with A. Gal, Ch. Hanhart, V. Kukulin and G. J. Wagner on this issue. We are particularly indebted to L. Alvarez-Ruso for using his code. This work has been supported by DFG (CL 214/3-2) and STFC (ST/L00478X/1) as well as by the Polish National Science Centre through the grant 2016/23/B/ST2/00784.

[1] W. Brodowski *et al.*, Phys. Rev. Lett **88** (2002) 192301
[2] J. Johanson *et al.*, Nucl. Phys. A **712** (2002) 75
[3] J. Pätzold *et al.*, Phys. Rev. C **67** (2003) 052202
[4] T. Skorodko *et al.*, Eur. Phys. J. A **35** (2008) 317
[5] T. Skorodko *et al.*, Phys. Lett. B **679** (2009) 30
[6] F. Kren *et al.*, Phys. Lett. B **684** (2010) 110 and Phys. Lett. B **702** (2011) 312; arXiv:0910.0995[nucl-ex]
[7] T. Skorodko *et al.*, Phys. Lett. B **695** (2011) 115
[8] T. Skorodko *et al.*, Eur. Phys. J. A **47** (2011) 108
[9] M. Bashkanov *et. al.*, Phys. Rev. Lett. **102** (2009) 052301.
[10] P. Adlarson *et al.*, Phys. Lett. B **706** (2012) 256
[11] S. Abd El-Samad *et al.*, Eur. Phys. J. A **42** (2009) 159
[12] S. Abd El-Bary *et al.*, Eur. Phys. J. A **37** (2008) 267
[13] P. Adlarson *et. al.* Phys. Rev. Lett **106** (2011) 242302.
[14] P. Adlarson *et al.*, Eur. Phys. J. A **52** (2016) 147
[15] P. Adlarson *et al.*,Phys. Lett. B **721** (2013) 229
[16] P. Adlarson *et al.*, Phys. Rev. C **88** (2013) 055208
[17] P. Adlarson *et al.*, Phys. Lett. B **743** (2015) 325
[18] G. Agakishiev *et al.*, Phys. Lett. B **750** (2015) 184
[19] A. P. Jerusalimov *et al.*, Eur. Phys. J. A **51** (2015) 83
[20] H. Clement, M. Bashkanov and T. Skorodko, *Phys. Scr.* T 166 (2015) 014016
[21] P. Adlarson et al., Phys. Rev. Lett **112** (2014) 202301.
[22] P. Adlarson et al., Phys. Rev. C **90** (2014) 035204.
[23] R. L. Workman, W. J. Briscoe and I. I. Strakovsky, Phys. Rev. C **93** (2016) 045201
[24] F. J. Dyson and N.-H. Xuong, Phys. Rev. Lett. **13** (1964) 815
[25] L. Alvarez-Ruso, E. Oset, E. Hernandez, Nucl. Phys. A **633** (1998) 519 and priv. comm.
[26] X. Cao, B.-S. Zou and H.-S. Xu, Phys. Rev. C **81** (2010) 065201
[27] A. V. Anisovich *et al.*, Eur. Phys. J. A **48** (2012) 15
[28] K. A. Olive *et. al.* (PDG), Chin. Phys. C **38** (2014) 090001.
[29] A. Gal and H. Garcilazo, Nucl. Phys. A **928** (2014) 73
[30] L. G. Dakhno *et. al.*, Sov. J. Nucl. Phys. **37** (1983) 540
[31] C. D. Brunt, M. J. Clayton and B. A. Wetswood, Phys. Rev. **187** (1969) 1856
[32] F. Shimizu *et al.*, Nucl. Phys. A **386** (1982) 571
[33] V. V. Sarantsev *et al.*, *Phys. At. Nucl.* **70** (2007) 1885
[34] A. M. Eisner *et al.*, Phys. Rev. **138** (1965) B670

[35] E. Pickup, D. K. Robinson and E. O. Salant, Phys. Rev. **125** (1961) 2091
[36] T. Tsuboyama *et. al.*, Phys. Rev. C **62** (2000) 0340011
[37] Ch. Bargholtz *et. al.*, Nucl. Instrum. Methods A **547** (2005) 294.
[38] H. H. Adam *et. al.*, arXiv:nucl-ex/0411038 (2004).
[39] P. Adlarson *et. al.*, arXiv:1803.03192 [nucl-ex]
[40] N. Hoshizaki, Prog. Theor. Phys. **89** (1993) 251
[41] R. A. Arndt, J. S. Hyslop and L. D. Roper, Phys. Rev. D **35** (1987) 128
[42] H. Clement, Prog. Part. Nucl. Phys. **93** (2017) 195
[43] M. Bashkanov, H. Clement and T. Skorodko, Nucl. Phys. A **958** (2017) 129
[44] S. Abd El-Samad *et. al.*, Eur. Phys. J. A **30** (2006) 443
[45] V. Komarov *et. al.*, Phys. Rev. C **93** (2016) 065206