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

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Exclusive measurements of the quasifree $pp \to pp\pi^+\pi^-$ 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.

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Introduction.—Multiquark states like tetra-, penta-, and hexaquark (dibaryon) systems, be they of compact or moleculelike strcuture, are a topical issue at present, extending largely our quark-based view of hadrons [1]. The existence of dibaryons has far-reaching consequences, e.g., for the formation of neutron stars [2]. Within systematic studies of two-pion production in nucleon-nucleon (NN) collisions at CELSIUS [3–11] and COSY [12–19], the first clear-cut evidence for a dibaryon resonance with $I(J^P) = 0(3^+)$ was observed recently in the $pn \to d\pi^0\pi^0$ reaction [11,15,16]. Subsequent measurements of all relevant two-pion production channels [17–22] revealed that all channels which contain isoscalar contributions exhibit a signal of this resonance—now called $d^*(2380)$ after observation of its pole in pn scattering [23–25]. Its structure is presently heavily disputed in various theoretical investigations [26–29]. Remarkably, it corresponds very well to $D_{IJ} = D_{03}$, predicted already in 1964 by Dyson and Xuong [30] as one of six nonstrange dibaryon states. Other members of that dibaryon multiplet are the deuteron ground state (D_{01}) and the virtual $^1S_0$ state (D_{10}), as well as the ΔN threshold states D_{12} and D_{21}—with the latter of these being still purely hypothetical. But recent state-of-the-art Faddeev calculations also predict the existence of these states [31].

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 [32,33]. 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 [34,35] 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) [9]—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 now come out much too low (see dashed line in Fig. 1). The reason is the underlying isospin relations between the various two-pion production channels. The purely isospin-based prediction obtained from isospin decomposition of pp-induced two-pion production [7] is shown by the shaded band in Fig. 1. The small differences between model calculation and isospin prediction are due to the neglect of small terms in the latter. For details, see Ref. [36].

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 [30] and recently calculated by Gal and Garcilazo [31].

Since all $pp \to pp\pi^+\pi^-$ data beyond 0.8 GeV stem from early low-statistics bubble-chamber measurements [37–43], it appeared appropriate to reinvestigate this region by exclusive and kinematically complete measurements.

Experiment.—The $pp \to pp\pi^+\pi^-$ reaction was measured by the 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 [44,45]. By exploiting the quasifree scattering process $pd \to pp\pi^+\pi^- + n_{\text{spectator}}$, 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.

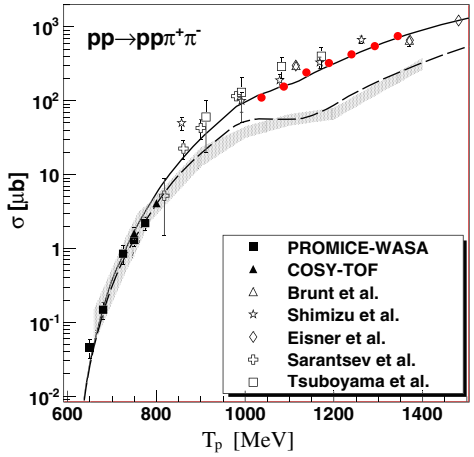

FIG. 1. Total cross section in dependence of the incident proton energy T_p for the reaction $pp \to pp\pi^+\pi^-$. The solid dots show results from this work. Other symbols denote results from previous measurements [3–5,14,37–41]. The shaded band displays the isospin-based prediction. The dashed line gives the modified Valencia calculation [9]. 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.

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

That way, the nonmeasured spectator four-momentum could be reconstructed by a kinematic fit with one overconstraint. 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 the kinematical fit has been 1.1%. In total, a sample of about 26 000 $pp\pi^+\pi^-$ events has been selected, which satisfy all cuts and conditions.

Efficiency and acceptance corrections of the data have been performed by MC simulations of the 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 and 3 give an 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 quasifree single-pion production process $pd \to pp\pi^0 + n_{\text{spectator}}$ to previous bubble-chamber results for the $pp \to pp\pi^0$ reaction [38,40]. 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. [36].

Results and discussion.—In order to determine the energy dependence of total and differential cross sections for the quasifree 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) [3–5,14,37–41]. Our data for the total cross section are in reasonable agreement with the earlier measurements.

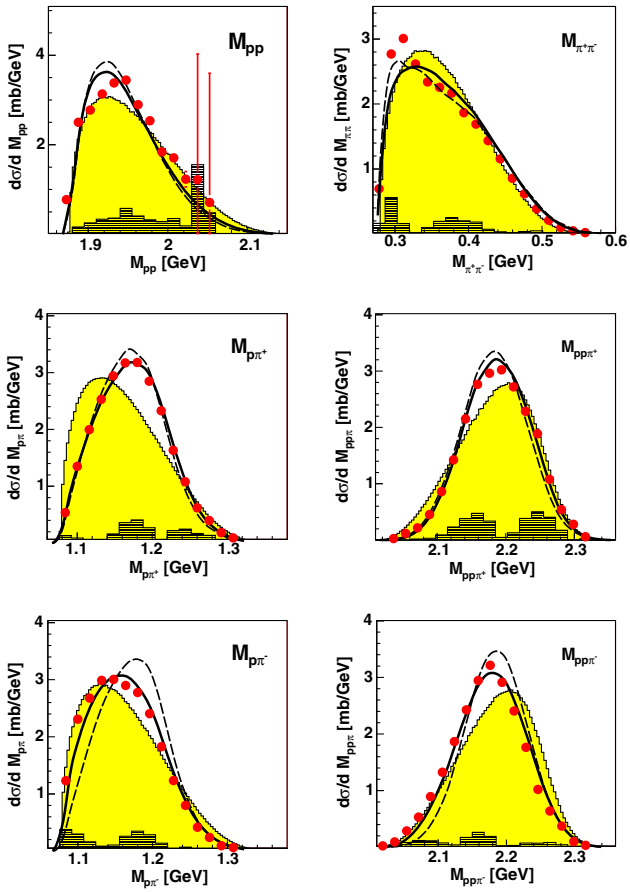

FIG. 2. Differential distributions of the $pp \to pp\pi^+\pi^-$ reaction in the region $T_p = 0.9$–1.3 GeV for the invariant masses M_{pp} (top left), $M_{\pi^+\pi^-}$ (top right), $M_{p\pi^+}$ (middle left), $M_{pp\pi^+}$ (middle right), $M_{p\pi^-}$ (bottom left), and $M_{pp\pi^-}$ (bottom right). 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, and dashed lines show modified Valencia calculations [9,32]. The solid lines include the process $pp \to D_{21}\pi^- \to pp\pi^+\pi^-$. All calculations are normalized in area to the data.

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 they underpredict substantially the data at higher energies. The reason is that by isospin relations, the $pp\pi^0\pi^0$ and $pp\pi^+\pi^-$ channels have to behave qualitatively similarly, 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 [9] is reproduced by any such model calculation, then the $pp\pi^+\pi^-$ channel also has to behave such (shaded band in Fig. 1); if not, a new strong and very selective ρ channel $\pi^+\pi^-$ production process enters [36].

Next, we consider the differential cross sections. For a four-body, axially symmetric final state there are seven independent differential observables. For a better

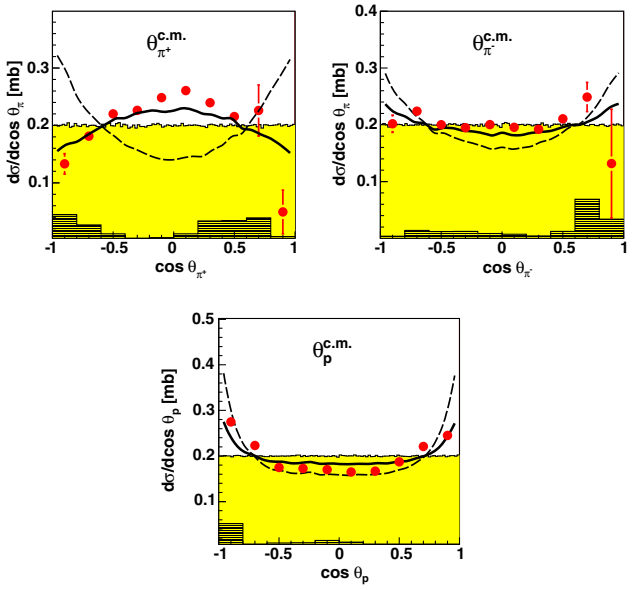

FIG. 3. The same as Fig. 2, but for the c.m. angles of positive and negative pions $\theta^{\mathrm{c.m.}}_{\pi^+}$ and $\theta^{\mathrm{c.m.}}_{\pi^-}$, respectively, as well as protons $\theta^{\mathrm{c.m.}}_{p}$.

discussion of the physics issue, we choose to show in this Letter nine differential distributions, namely those for the center-of-mass (c.m.) angles for protons and pions, denoted by $\theta^{\mathrm{c.m.}}_{p}$, $\theta^{\mathrm{c.m.}}_{\pi^+}$, and $\theta^{\mathrm{c.m.}}_{\pi^-}$, 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 and 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 and 3). With the exception of $\theta^{\mathrm{c.m.}}_{\pi^+}$, $M_{p\pi^-}$, 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 and 3.

The proton angular distribution is strongly forward-backward peaked, as expected for a peripheral reaction process. The π^- angular distribution is rather flat, in tendency slightly convex curved, as is 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 [36].

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 the 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.

This model-independent observation supported by the failure of the modified Valencia calculation to describe properly both the total cross section and the differential distributions suggests that the t-channel $\Delta\Delta$ process is not the leading one here.

It appears 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. Since there is no baryon excitation, which could cure these problems here, and since the discrepancy between data and the modified Valencia description opens up scissorlike around $T_p \approx 0.9$ GeV, it matches the opening of a new channel, where a ΔN system is produced associatedly with another pion. In addition, the ΔN system has to be isotensor, in order to have the Δ excitation only in the $p\pi^+$ system as observed in the data. Such a state with the desired properties could be the isotensor D_{21} state with $I(J^P) = 2(1^+)$ predicted already by Dyson and Xuong [30] 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 [46,47], 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. [48].

Due to its isospin, $I = 2$ D_{21} cannot be reached directly by the initial pp collisions, but can 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 [30]—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. [36,49] by adding the D_{21} production on the amplitude level. The D_{21} resonance can be formed together with an associatedly produced pion in either a 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 $\sin\theta^{\mathrm{c.m.}}_{\pi}$ 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 being associated simultaneously with a flat 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 and 3), in particular also of the $\theta^{\mathrm{c.m.}}_{\pi^+}$, $M_{p\pi^-}$, and $M_{pp\pi^-}$ distributions. Since the D_{21} decay populates only Δ^{++}, its reflection 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 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 [50,51]. Also in this case, it turned out that the reason for it was the excitation of resonances in the ΔN system [51] causing a proton spin-flip situation as in our case here.

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 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 the 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 [30]. Both the mass and width are just slightly smaller than those calculated by Gal and Garcilazo [31].

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 by use of the quasifree process $pd \to pp\pi^+\pi^- + n_{\text{spectator}}$. 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 $\theta_{\pi^-}^{\text{c.m.}}$ distributions are observed to be strikingly different from their counterparts, the $M_{p\pi^+}$, $M_{pp\pi^+}$, and $\theta_{\pi^+}^{\text{c.m.}}$ 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.

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