Systematic Study of Two-Pion Production in $NN$ Collisions — from Single-Baryon to Di-Baryon Excitations

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Abstract

The two-pion production in nucleon-nucleon collisions has been studied by exclusive and kinematically complete experiments from threshold up to $T_p = 1.36$ GeV at CELSIUS-WASA. At near-threshold energies the total and differential distributions for the $\pi^+\pi^-$ and $\pi^0\pi^0$ channels are dominated by Roper excitation and its decay into $N\sigma$ and $\Delta\pi$ channels. At beam energies $T_p > 1.1$ GeV the $\Delta\Delta$ excitation governs the two-pion production process. In the $\pi^+\pi^+$ channel evidence is found for the excitation of a higher-lying $I=3/2$ resonance, favorably the $\Delta(1600)$. The isovector fusion processes leading to the deuteron and to quasi-stable $^2\text{He}$, respectively, exhibit no or only a modest ABC-effect, i.e. low-mass enhancement in the $\pi\pi$-invariant mass spectrum, and can be described by conventional $t$-channel $\Delta\Delta$ excitation. On the other hand, the isoscalar fusion process to the deuteron exhibits a dramatic ABC-effect correlated with a narrow resonance-like energy dependence in the total cross section with a width of only 50 MeV and situated at a mass 90 MeV below the $\Delta\Delta$ mass.

1 Introduction

The $\pi\pi$ production in isoscalar, isovector and isotensor $\pi\pi$ channels has been systematically studied in nucleon-nucleon ($NN$) collisions at CELSIUS both in double-pionic fusion reactions and in reactions, where the two participating nucleons do not fuse into a final nuclear bound system.

According to theoretical predictions the $NN$ initiated two-pion production should be dominated by excitation and decay of resonances in the course of the reaction process. In the channels, where two pions can be in the scalar-isoscalar state, the main production mechanism at low energies is expected to be the Roper excitation. This provides the unique possibility
to study the excitation of the still puzzling Roper resonance and its subsequent decay into the $N\pi\pi$ system at low incident energies, where no other competing processes are expected to contribute significantly.

At energies $T_p \geq 1.1$ GeV the mutual excitation of both nucleons into their first excited state, the $\Delta$ resonance, is expected to take over. Note that the latter process can not take place in photo- or pion-induced single-baryon reactions. Hence the NN collision process is uniquely suited for the study of the $\Delta\Delta$ excitation, which may have a large impact on the question regarding the interaction between two excited nucleons.

The two-pion production in double-pionic fusion reactions deals with the problem of an unexpected low-mass enhancement in the $\pi\pi$ invariant mass ($M_{\pi\pi}$) spectrum, known as ABC effect. This effect has been an intriguing puzzle all the time since its discovery 50 years ago by Abashian, Booth and Crowe [2] and is named after the initials of these authors. Follow-up experiments [3, 4, 5, 6, 7, 8, 9, 10, 11] revealed this effect to be of isoscalar nature with regard to the $\pi\pi$ system and to happen solely in cases, where the two-pion production process leads to a bound nuclear system. With the exception of low-statistics bubble-chamber measurements all previous experiments carried out on this issue have been inclusive measurements conducted preferentially with single-arm magnetic spectrometers for the detection of the emitted fused nuclei. Since the ABC effect occurred at beam energies corresponding roughly to the excitation energy of two $\Delta$s, the ABC effect was interpreted [10, 11, 12, 13, 14, 15, 16] by $t$-channel $\Delta\Delta$ excitation in the course of the reaction process leading to both a low-mass and a high-mass enhancement in the isoscalar $M_{\pi\pi}$ spectra. In fact, the missing momentum spectra from inclusive measurements have been in support of such predictions.

2 Experiment

Exclusive measurements of the reactions $pp \rightarrow pp\pi^0\pi^0$, $pp \rightarrow pp\pi^+\pi^-$, $pp \rightarrow pn\pi^+\pi^0$, $pp \rightarrow nn\pi^+\pi^+$, $pp \rightarrow d\pi^+\pi^0$ and $pd\rightarrow pd\pi^0\pi^0$ have been carried out at beam energies in the range $T_p = 0.65 - 1.36$ GeV at the CELSIUS storage ring using the 4$\pi$ WASA detector setup [17] including the pellet target system. The $pd\rightarrow pd\pi^0\pi^0$ reaction proceeds as quasifree $pn\rightarrow d\pi^0\pi^0$ reaction with a spectator proton of very small momentum in the lab system.

For the reactions under consideration forward going charged pions, protons, neutrons and deuterons have been detected in the forward detector and identified by the $\Delta E-E$ technique using corresponding information from forward window, quirp, range and veto hodoscopes, respectively. Charged pions
as well as gammas (from $\pi^0$ decay) have been detected in the central part of WASA, which contains a solenoid magnetic field with a mini drift chamber as well as the electromagnetic calorimeter. The direction of neutrons could be measured in most cases by their hit pattern resulting from recoil protons in forward and central detectors.

With the exception of spectator protons and of neutrons the four-momenta of all emitted particles have been measured. That way in all cases the full events could be reconstructed with 1 – 5 overconstraints and subjected to kinematic fits.

3 Results

3.1 \( pp \to NN\pi\pi \)

The two-pion production in pp-collisions has been measured from threshold up to \( T_p=1.36 \) GeV. Total as well as differential cross sections have been obtained for \( pp\pi^+\pi^- \) \[18, 19, 20, 21\], \( pp\pi^0\pi^0 \) \[18, 21\], \( pn\pi^+\pi^0 \) \[18, 21\] and also \( nn\pi^+\pi^+ \) \[21\] channels.

At low incident energies, i.e. \( T_p \leq 0.9 \) GeV, the data on the \( \pi^+\pi^- \) and \( \pi^0\pi^0 \) channels have been successfully explained by excitation and decay of the Roper resonance \[19, 20, 21, 22\]. However, the analysis of the near-threshold \( \pi^+\pi^- \) and \( \pi^0\pi^0 \) production, where the differential observables are exceptionally sensitive to the interference between the two Roper decay branches, provides a ratio of approximately 1:1 for the decay branching into \( N\sigma \) and \( \Delta\pi \) channels at a Breit-Wigner mass of 1440 MeV \[22, 23\]. This branching ratio is in very good agreement with the value obtained by the Bonn-Gatchina group in their partial-wave analysis \[24\], but a factor of 4 larger than quoted in PDG \[25\], where a ratio of 1:4(2) is quoted. Note that at the pole mass for the Roper resonance, i.e. at \( m \approx 1370 \) MeV, this branching ratio transforms even into 4:1, which points to a dominantly monopole nature of the Roper excitation.

At incident energies above 1 GeV, where the t-channel \( \Delta\Delta \) excitation should take over, the data for the \( \pi^+\pi^- \) and \( \pi^0\pi^0 \) channels change drastically. Indeed the \( \Delta\Delta \) mechanism is identified by observing the simultaneous excitation of \( \Delta^{++} \) and \( \Delta^0 \) in the appropriate \( M_{\pi^+\pi^-} \) and \( M_{\pi^0\pi^0} \) spectra. However, at the same time we observe \[26\] a phase-space like behavior in the measured \( M_{\pi^+\pi^-} \) and \( M_{\pi^0\pi^0} \) spectra rather than the predicted \[1\] double-hump structure. Moreover, the predicted \( \pi^0\pi^0 \) total cross section rises smoothly with increasing the incident energy, whereas the measured total cross section levels off in the energy range 1.0-1.2 GeV before it starts rising again for \( T_p \).
Figure 1: Differential distributions of the invariant masses $M_{\pi^0\pi^0}$ (left) and $M_{\pi\pi}$ (right) for the $pp \rightarrow pp\pi^0\pi^0$ reaction at $T_p = 1.3$ GeV. Solid dots represent the experimental results of this work. The shaded areas denote the phase space distributions. The dotted curves show the original predictions of Ref. [1], whereas the dashed lines give the same calculation, however, corrected for the proper Roper contributions as obtained from the analysis of differential data at lower beam energies [19, 20, 22, 23] and from isospin decomposition [21]. The solid lines give the $t$-channel $\Delta\Delta$ calculations in the framework of Risser and Shuster [12], which is based on pion-exchange solely. All theoretical curves are normalized in area to the data.

\[ 1.2 \text{ GeV} \] [21]. This partial failure of the theoretical description in the $\Delta\Delta$ region is presently still under investigation. Possibly the $\rho$-exchange used in Ref. [11] is the major reason for this failure. This is supported by the fact that the $t$-channel $\Delta\Delta$ calculations in the framework of Risser and Shuster [12], which are based on pion-exchange solely, provide a superior description of the data. As an example Fig. 1 shows the invariant mass spectra $M_{\pi^0\pi^0}$ and $M_{\pi\pi}$ from the $pp \rightarrow pp\pi^0\pi^0$ reaction at $T_p = 1.3$ GeV.

Another even more severe shortcoming of the calculations of Ref. [11] is observed in the $nn\pi^+\pi^+$ channel, where the cross section turns out to be a factor of 5 larger than predicted. Under the assumption that the $\Delta\Delta$ excitation is the dominant process in this channel, too, we would expect the $\pi^0\pi^0$ cross section to be four times larger than the $\pi^+\pi^+$ cross section by use of isospin relations. At $T_p = 1.1$ GeV we observe this ratio, however, to be close to unity [21]. We note that our results for the $\pi^0\pi^0$ and $\pi^+\pi^+$ cross sections are in good agreement with previous bubble chamber data [27, 28].

In order to be independent of model assumptions we have carried out an isospin decomposition of the total cross sections [21]. As a result we obtained an amplitude for the isoscalar $\pi\pi$ channel, which is in good agreement with
the theoretical predictions for the Roper excitation at energies $T_p < 1$ GeV. For higher energies the theoretical cross section for the Roper excitation process appears to be largely overestimated.

Since the isotensor $\pi\pi$ channel cannot be described by just the $\Delta\Delta$ excitation and small non- and semi-resonant contributions [1], contributions from higher-lying $I=3/2$ resonances have to be considered as a possible way out [21]. The next higher-lying candidate resonance is the $\Delta(1600)$. Since it has a large width of about 350 MeV and preferably decays via the $\Delta(1232)$, it may contribute strongly to the isotensor cross section and also to the isovector part. With the aid of this excitation we obtain a good description of all $pp \to NN\pi\pi$ total cross section data up to $T_p=1.5$ GeV.

3.2 $NN \to {}^2\text{He}\pi\pi$ and $NN \to d\pi\pi$

If we constrain the relative momenta of the protons emitted in the $pp \to pp\pi^0\pi^0$ reaction by a cut $M_{pp} < 2m_p + 10$ MeV, then we select the emitted $pp$ system to be at very small energy and in relative s-wave, i.e. in a quasi-bound $^2\text{He}$ final state. That way we obtain the transition to double-pionic fusion. Indeed, if we apply this cut to our data, then we obtain a double-hump structure in the $M_{\pi^+\pi^-}$ spectrum as predicted by the $t$-channel $\Delta\Delta$ calculations of the early theoretical interpretation of the ABC effect [12]. Also the recent COSY-ANKE data [29] for the $pp \to ppX$ reaction with $M_{pp} < 2m_p + 3$ MeV in a restricted angular range are well accounted for by this process.

Having understood the transition from the two-pion production process for unbound $NN$ systems to the quasibound one, we next investigate this process to the really bound $NN$ system by studying the $pp \to d\pi^+\pi^0$ reaction. Since we have here the production of an isovector pion pair, Bose symmetry requires this system to be in relative p-wave. This means, however, that the intensity at small $M_{\pi^+\pi^0}$ must be suppressed and no low-mass enhancement is to be expected. Indeed, our measurements of this reaction at $T_p = 1.1$ GeV exhibit no ABC effect and all differential data are in good agreement with the conventional $t$-channel $\Delta\Delta$ process [30]. This process gives also full account for the energy dependence of the total cross section of this reaction, which exhibits a broad resonance-like structure of width $\approx 230$ MeV, i.e. twice the $\Delta$ width, and peaking at twice the $\Delta$ mass.

The situation gets drastically different, when switching from the isovector $pp$ incident channel to the isoscalar $pn$ incident channel [31, 32, 33]. The total cross section of the $pn \to d\pi^0\pi^0$ reaction exhibits a strong and narrow resonance structure. In the very recent high-statistics measurements with the WASA detector at COSY [33] a width as narrow as 50 MeV is observed,
i.e. nearly five times smaller than expected from the conventional $t$-channel $\Delta \Delta$ process. Moreover this structure does not peak at twice the $\Delta$ mass, but 80 MeV below it. In the region of this resonance structure – and only in this region – the $M_{\pi^0\pi^0}$ spectrum exhibits a huge low-mass enhancement, much larger than expected from the conventional $t$-channel $\Delta \Delta$ process. Also in contradiction to this process no significant high-mass enhancement is found. Though these findings are at variance with the conventional $t$-channel $\Delta \Delta$ process the Dalitz plots clearly show the mutual excitation of two $\Delta$ states in the course of the reaction.

4 Summary and Conclusions

For the two-pion production induced by $pp$ collisions data are now available for all exit channels from threshold up to the region of the $\Delta \Delta$ excitation. Many of these data have been obtained by exclusive and kinematically complete measurements, which provide both total and differential cross sections. The bulk properties of these data are basically well accounted for by $t$-channel processes leading to the associated production of Roper and $\Delta(1600)$ resonances, respectively, or to the mutual excitation of both nucleons into the $\Delta$ state each. In the $\Delta \Delta$ region we find some discrepancy between the observed differential distributions and the calculations of ref. [1]. The calculations in the framework of Risser and Shuster [12], which only account for simple pion exchange, give a superior description. This points to a problem connected with $\rho$ exchange and/or short-range correlations as handled in the calculations of Ref. [1].

Whereas the two-pion production induced by isovector $NN$ collisions appears to be reasonably well understood by conventional $t$-channel processes, the situation is fundamentally different in the two-pion production induced by isoscalar $pn$ collisions. Unfortunately there are no or no high-quality data for the non-fusion channels — for obvious reasons, since they are very hard to attack experimentally. However, there are now high-quality and high-statistics data available for the quasi-free $pn \rightarrow d\pi^0\pi^0$ reaction both from CELSIUS [31, 32] and in particular now also from COSY [33]. In both cases we find a huge low-mass enhancement in the $M_{\pi^0\pi^0}$ spectrum (ABC effect), which is correlated with a narrow resonance-like structure in the total cross section. From isospin relations for the conventional $t$-channel $\Delta \Delta$ process, which has been demonstrated to work in the $pp$ induced two-pion production, we find that the latter process cannot account for these intriguing features in the isoscalar $pn$ channel even in a qualitative way.

From these observations we are led to conclude that the observed reso-
nance must be due to an unconventional process, which proceeds through the mutual excitation of two nucleons into the \(\Delta\Delta\) system, possibly in a kind of doorway mechanism. Due to the antisymmetry condition for this system its quantum numbers can only be \(I(J^P) = 0(1^+)\) or \(0(3^+)\), if we assume the \(\Delta\Delta\) system to be in relative s-wave — which again is very plausible, since the resonance is far below the nominal \(\Delta\Delta\) threshold. From the angular distributions we infer some evidence for the larger spin value. The detailed analysis of this matter is, however, still in progress.

The situation that the ABC effect – well-known now since 50 years – is associated with a narrow resonance structure in the total cross section comes as a big surprise. It was not predicted by any theoretical considerations. If true that this process proceeds via the s-channel, then we see here the first manifestation of a genuine resonance in the dibaryon system — as predicted and searched for also since nearly 50 years. We note that resonances in the baryon-baryon system, in particular in the \(\Delta\Delta\) system, actually have been predicted by various quark model calculations \cite{34, 35, 36, 37, 43, 44}.

Finally we note that meanwhile we also carried out exclusive and kinematically complete measurements of the double-pionic fusion to \(^3\)He and \(^4\)He. Again we observe huge low-mass enhancements in the \(M_{\pi^0\pi^0}\) spectra \cite{45, 46, 47}. This means that this resonance is obviously robust enough to survive even in the nuclear medium.

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